PREDICTIVE ENERGY MANAGEMENT AND CONTROL FOR RENEWABLE ENERGY PLUS BATTERY ENERGY STORAGE SYSTEMS

By

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AUTHOR'S DECLARATION

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Irtaza Mohammad Syed, Doctor of Philosophy (2016), Electrical and Computer Engineering, Ryerson University

ABSTRACT

Renewable energy (RE) is one of the solutions to rising energy demands and growing environmental concerns. However, due to the intrinsic intermittency of RE resources, generated power is irregular and the supplied energy is intermittent. Intermittency renders RE systems non-dispatchable and can cause energy surplus and shortage. RE surplus can translate into curtailment and shortage can cause supply and demand issues. Curtailment wastes RE and supply and demand issues result in loss of load compromising service quality and system reliability.

Battery energy storage system (BESS) is the widely accepted solution to mitigate the negative impacts of intermittency. However, this solution has relied on the conventional energy management and control (EMC) techniques that: 1) cause curtailment, 2) cause supply and demand issues, 3) cannot exploit BESS potential, 4) use RE passively (if and when available), and (5) are suitable only for readily dispatchable generation systems.

This work proposes predictive EMC (PEMC) over conventional EMC (CEMC) to predictively perform EMC of RE systems (photovoltaic (PV) and wind) plus BESS (RE-BESS). PEMC predictively optimizes resources, makes control decisions and manages RE system operations based on the present and future (forecasted) load (or commitments) and RE potential over 24hours horizon. PEMC 1) minimizes curtailment (maximize RE proportions), 2) minimizes supply and demand issues, 3) exploits BESS potential, 4) uses RE proactively (instead of operating on the mercy of weather), 5) compensates for forecast errors, and 6) maximizes savings (or revenue).

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LIST OF ABBREVIATIONS/ACRONYMS

2WC	Two Way Communication
BESS	Battery Energy Storage System
CEMC	Conventional Energy Management and Control
Curl	Curtailment
DAC	Day Ahead Commitment
DD	Dispatch Down
DOD	Depth of Discharge
DU	Dispatch Up
EMC	Energy Management and Control
ES	Energy Storage
FFG	Fossil Fuel Generator
HEE	Hourly Energy Estimate
IESO	Independent Electricity System Operator
kW	kilo Watt
kWh	kilo Watt hour
MW	Mega Watt
MWh	Mega Watt hour
NPEMC	No PEMC
NRC	Non Residential Customers
PB	Battery Power
PBF*	BESS forecasted power reference for charge or discharge

PD	Load (or Demand) Power
PDF	Forecasted load power or demand
PEMC	Predictive Energy Management and Control
PEMCC	Predictive Energy Management, Control & Communication
PG	Grid power
PSH	Peak Sun Hours
PV	Photovoltaic
PVF	Forecasted PV potential
RC	Residential Customers
RE	Renewable Energy
RE-BESS	RE plus BESS
TOU	Time of Use
WAPDA	Water And Power Development Authority

NOMENCLATURE

Cost

C_i	Energy hurly cost (Canadian dollars)
C_m	Energy hourly cost in mid-peak period (Canadian dollars)
C_o	Energy hourly cost in off-peak period (Canadian dollars)
C_p	Energy hourly cost in on-peak period (Canadian dollars)
$R_{on\text{-}pk}$	On-peak price (Canadian dollars)
$save	Savings (Canadian dollars)
YCC	Yearly consumption cost (Canadian dollars)

Energy

E_{ACT}	Actual energy delivered (Wh)
E_{BESS}	BESS energy (Wh)
E_{Bf}	BESS energy final (Wh)
E_{Bi}	BESS energy initial (Wh)
$E_{B\text{-}DAC}$	BESS energy required for 24h (Wh)
$E_{BF}(k)$	Forecasted BESS energy at k_{th} instant (Wh)
$E_{BF}(k-1)$	BESS energy at k_{th}-1 instant (Wh)
$E_{B\text{-}max}$	BESS energy upper limit (Wh)
$E_{B\text{-}min}$	BESS energy lower limit (Wh)
$E_{BPDF@OP}$	BESS energy for present + forecasted load in on-peak period (Wh)
E_D	Load shedding period demand (Wh)
E_{DAC}	DAC committed energy (Wh)

E_{EN}	Yearly energy from grid (Wh)
E_{HEE}	Hourly energy estimate (Wh)
E_{PV}	PV system yearly energy yield (Wh)
E_{W}	Wind Energy (Wh)
E_{WD}	Wind energy delivered (Wh)
E_{WDAC}	Wind DAC Energy (Wh)
PV_{year}	Yearly PV irradiance potential (Wh)

IESO Dispatch Instructions

DD	Dispatch Down
DU	Dispatch Up
DI-	Dispatch instruction in terms of DD
DI+	Dispatch instruction in terms of DU

Interval/Time

d	Days
Δt	Time interval (minutes)
k	k_{th} instant or present interval (minutes)
k+1	k_{th}+1 instant or next future interval (minutes)
k+n	k_{th}+n instant or k+n future interval (minutes)
Ls_{f}	Load shedding period end
Ls_{i}	Load shedding period start
hr_{pk}	On-peak hours (hour)
t	time (minutes)

Power

G	Solar irradiance (W/m2)
P_B	BESS Power (W)
$P_{BF}(k)$	Forecasted BESS status at k_{th} instant (W)
P_{B-max}	BESS max charge or discharge power (W)
P_{B-min}	BESS min charge or discharge power (W)
$P_{CE}(k)$	Error Power at k (W)
$P_{CF}(k)$	Forecasted curtailed (or shortage) power (W)
$P_{DF}(k)$	Forecasted load or demand at k_{th} instant (W)
P_g	Grid power (W)
$P_{gF}(k)$	Forecasted grid power at k_{th} instant (W)
P_L	Grid lower power limit (W)
P_O	Output power (W)
P_{O-max}	Maximum output power (W)
P_{OF}	Forecasted output power (W)
$P_{OF(k-1)}$	Forecasted output power at k-1 instant (W)
P_{pd}	Peak demand or load at any instant (W)
$P_{PVF}(k)$	Forecasted PV potential at k_{th} instant (W)
P_U	Grid upper power limit (W)
PV_{size}	PV system size (W)
P_W	Wind power (W)
P_{WF}	Wind forecasted power (W)
P_{W-min}	Minimum wind power (W)
P_{W-max}	Maximum wind power (W)
$P_{W-rated}$	Wind rated power (W)

P_{WT}	Wind Turbine Power (W)
Y(k)	Predicted output at kth instant (W)

Wind Turbine

A	Swept area (m^2)
r	Radius (m)
ρ	Rho, air density (kg/m^3)
V	Wind velocity (m/s)

Dimensionless

C_p	Power co-efficient
D_f	Derate factor
D(k)	Direction Down at k
η	Efficiency
η_c	Charging efficiency
η_d	Discharging efficiency
R_{PA}	Real power adjustment factor
U	Control actions set
U(k)	Direction Up at k

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Environmental concerns and global warming, the ever growing prices of scarce and exhausting fossil fuels, increasing energy demand, lack of access to power and/or power grid, coupled with aging grid infrastructures, reliability and security concerns are all pushing towards renewable energy (RE). RE is abundant, naturally replenish-able, and has no or limited environmental footprints. A number of technologies have been developed to convert RE resources, such as wind and solar, into usable form of energy in general and electricity in particular. Individuals, businesses, utility companies and governments, all are heavily investing in this field to keep the future grid reliable, cost-effective, and environmentally friendly. However, RE systems are inherently intermittent and non-dispatchable, and cause short term intermittency resulting into irregular (fluctuating) power and medium to long term intermittency translating into RE curtailment and supply and demand balance issues.

As pointed out earlier RE resources are geography dependent and non-dispatchable, and pose challenges in terms of intermittency [1, 2]. Components sizing, placement, optimal scheduling, unit commitment, power quality, voltage and frequency control, load sharing and demand side management through conventional EMC (CEMC), a passive non-predictive technique, can play a role in improving the functionality of RE systems [3-9]; however, most of the time these solutions rely on fossil fuel generators (FFG), grid, and/or energy storage (ES) for energy backup and control. FFG 1) require continuous operation and maintenance, 2) incur operational cost, and 3) cause greenhouse gas emissions. Power import from a grid, on the other hand, 1) is possible only if the grid is accessible, 2) has continuously rising associated cost, and 3) may get expensive at times if utility has time-of-use (TOU) tariff [10]. ES can be used to store surplus and supply shortage; however, a huge ES is required to ensure reliable RE supply without supply and demand issues, which may increase the capital investment and require maintenance. Alternatively, RE curtailment is accepted as norm and load shedding is allowed, due to intermittency. RE curtailment wastes surplus energy while supply and demand compromises service reliability, rendering partial or full load without power.

Battery energy storage system (BESS) is seen as a reliable contender to resolve RE systems associated power quality and service reliability issues [11-15] on all levels from kilo-watt-hour (kWh) to mega-watt-hour (MWh) and for all applications from residential to utility scales. However, BESS is of little use in the RE systems with CEMC techniques [16], the passive solutions that can: 1) only use RE if and when available (mercy of weather), and 2) charge or discharge BESS in reaction to RE surplus or shortage at present. The size of BESS also plays a deterministic role in defining RE plus BESS (RE-BESS) system capabilities and limitations and often causes: 1) RE waste due to curtailment [16 – 28] upon RE surplus, and 2) supply and demand issues [17, 20 – 27] due to energy insufficiency upon RE shortage translating into loss of load. Mai et al. [16] report that curtailment can grow as much as 30%. In addition, CEMC does not exploit BESS potential thus either rely on huge BESS or resorts to load shedding with loss of load, adding to the cost or compromising service reliability. In short, CEMC techniques: 1) operate on the mercy of the weather, 2) often cause RE curtailment, 3) result in supply and demand issues, 4) are limited by the BESS storage size, 5) can perform in-time optimization only (without predictive optimization), 6) lack mechanism to counteract forecast errors, and 7) can provide only limited savings for the system's owner. With higher proportions of RE resources and CEMC techniques, RE systems curtailment, supply and demand balance, efficiency and power quality, all become even more complicated [8, 16, 27, 28]. In the following paragraphs we review the literature to reveal and emphasize the negative impacts of intermittency and insufficiency of CEMC in three distinct application scenarios as a representative of the issues outlined above.

A) Peak demand time-of-use consumption and cost

Peak demand, the highest amount of electricity consumed at any point in time during a day across the entire electrical network, usually falls within the time frame of 1-6 hours. Peak demand puts considerable stress on the electrical network, causing transmission constraints and increasing the risk of blackouts and brownouts. It also means higher energy cost for consumers. To prevent peak demands, the utility companies have opted for multipronged approaches; time-of-use (TOU) tariff is one such approach. TOU structure uses higher prices as an indirect approach to shape consumers' behaviour [29], reduce demand on the grid and maintain quality of service during the periods with peak demand. Consumers' adaption to the TOU structure by time-shifting their energy consumption creates a win-win situation for both the utility companies and consumers [29]. However, it is important to note that TOU tariff is not a deterministic solution, and since it depends on the consumers' behaviour, it is not guaranteed.

Energy storage (ES) units serve as backups to counteract the imbalance of supply and demand. ES application for power smoothing, power quality, and voltage control has been reported previously [30-33] with multiple technologies reported in [30, 34]. BESS has been sized and used to reduce residential peak demand [35]. Leadbetter and Swan [35] size BESS based on the residence's load profile simulated at 5-minute intervals and charged from grid during off-peak tariff time. Hossain and Iqbal [36] also propose BESS for profit from Net-Metering and Variable Rate Electricity by charging in off-peak and discharging in on-peak periods. Some researchers [37, 38] report sizing methodology of BESS for a consumer connected to the grid with variable rate and TOU tariff structures. Others however, completely ignored the role of renewable energy and thus relied on grid for charging BESS without local energy security and cushion against grid energy increasing prices [35 - 38]. Nagayoshi et al. [39] proposed PV integrated BESS peak reduction for an institutional setup. The utility company involved used 100 kW PV plus 345 kWh lead acid battery. The authors report a peak demand reduction of 7% without using TOU structure. Castillo-Cagigal et al. [40] proposed a semi-distributed electric demand side management system with PV generation for self-consumption enhancement. Electric demand side management was used to define house energy policy. Electric use by appliances was controlled to minimize energy from the grid without any optimization. Sun and colleagues [41] discuss the impacts of pre-cooling on reducing the peak demand and electricity cost without applying any optimization method or using TOU tariff. Doorman [42] proposed capacity subscription, restricting the consumers to pre-subscribed amount of capacity during peak hours. Consumers buy energy according to their anticipated demand and the utility company restricts their usage to that amount during peak demand period. This approach also requires human behaviour shaping as argued by many [29, 43, 44] and may cause service quality and reliability issues. Nghiem et al. [45] proposed green scheduling of control systems for peak demand reduction. In this approach the building's high voltage AC systems are scheduled to minimize their use during the peak hours and therefore reduce the energy cost significantly. In a similar way, Agnetis et al. [46] proposed load scheduling for electricity consumption optimization in residential sectors. None of the aforementioned studies however used predictive optimization or BESS advancement (or delay). Therefore, this work has selected this as a 1st case for application of PEMC.

B) Weak grid with periodic load shedding

Grids are seeing integration of RE systems on transmission as well as distribution levels. A variety of RE technologies, such as wind, solar, etc., have been integrated; however, only PV technology makes sense on a distribution level as it requires no fuel, involves no moving parts, and does not pollute the environment. Furthermore, it is scalable, cheap with prices continuing to decline, and requires inherently low maintenance that does not require a high level of technical skills or expertise.

Microgrid, a system with RE and/or conventional sources, energy storage and cluster of load that can operate in parallel with or independently from the main grid [47], is gaining popularity. In grid-tied mode, microgrid reliable operation requires an operating grid with stable voltage and frequency. However, BESS (and/or a FFG), is used for backup and reliable operation in standalone mode. In grid-tied mode the microgrid supplies surplus energy into grid and/or BESS when generation is greater than demand and retrieves from grid and/or BESS when demand is greater than generation. Similarly, microgrid in standalone mode uses energy generated and/or stored in BESS (and/or FFG) to supply for the load. Energy supply is even more important in standalone mode since a grid will not be available, either due to unplanned failure or planned periodic load shedding. However, the capability of microgrid to exploit available RE resources in standalone mode when grid fails is limited by the capacity of the BESS and load demand, which results in RE curtailment [16 – 28]. Curtailment wastes the freely available RE and the amount of curtailment increases dramatically for microgrid tied to a weak grid with load shedding. Unplanned load shedding may arise due to faults, loss of generation, switching errors, and lightning strikes, while planned load shedding may be due to grid maintenance or insufficient generation. Unplanned load shedding caused by faults are unpredictable and sporadic, while planned load shedding's are either infrequent and predictable for maintenance or periodic due to insufficient generation.

Predictive control has been reported for improving the system's power stability [48] and controlling the emergency voltage [49]. Predictive control has been proposed for controlling the frequency of power system [50] and for decentralized load frequency control in tough situations [51]. Predictive control based mitigation of cascaded failures is discussed in [52] and two-stage solution to prevent voltage collapse is discussed in [53]. Thermal overload alleviation using Predictive control is reported in [54], and predictive energy management and control system (PEMC) based dynamic energy management of RE integrated power systems are reported in [55]. Power electronic systems predictive control is discussed in [56] and PEMC based dynamic resources allocation is explored in [57]. Predictive control/PEMC application has been discussed for load shedding in power distribution in power systems [58], voltage stability during load shedding [59], and non-disruptive load shedding [60]. Predictive control/PEMC approach has been used for operation optimization of MG [61] and wind-battery microgrid [62]. However, none of the aforementioned studies has reported using predictive control or PEMC to ensure energy supply for local load, minimize curtailment, increase PV energy proportions locally and into the grid, and support a weak grid with planned periodic load shedding. Therefore, in this work these have been considered as potential applications of PEMC.

C) Irregular Power and Day Ahead Commitment Delivery

Solar and wind power are the fastest growing RE sources [63, 64], with solar power doubling every 2 years, reaching a total of 450 gigawatts by 2017 and wind power reaching a total of 1900 gigawatts by 2020 [64]. Between 2000 and 2010 the cumulative global renewable electricity capacity has grown 97% from 748 gigawatts to 1,470 gigawatts [65]. Wind for generating electricity is one of the key solutions to meet the ever growing demand and new environmental standards/codes. However, wind energy is inherently non-dispatchable due to irregular generation caused by the intermittent wind resources. Intermittency can be short or long term. Short term intermittency causes power fluctuations while long term intermittency causes energy supply issues. Intermittency impacts components sizing, placement, operations and control, energy supply and management, units scheduling and commitment, power quality and service reliability [3, 4].

Intermittent wind resources render wind energy, a non-dispatchable source of energy. Nameplate or rated capacity can only be relied upon under peak production conditions [11]. Irregular wind resources often cause energy supply and demand balance issues [66]. Energy shortage (ES) causes load shedding [17, 20 – 27, 66] while energy surplus causes curtailment and waste [16-28]. In

2014 alone, 376 gigawatt-hour of wind surplus energy was curtailed due to: 1) surplus baseload generation, 2) supply and demand balance issues, and 3) congestion along transmission lines [67]. Therefore, successful integration of WE into the grid requires solutions that solve both power and energy related issues.

Power fluctuations causing issues such as frequency fluctuations, voltage flickers, and system instability have been tackled with some sort of ES. Geographical dispersion [68], supervisory control with BESS and forecast [69], and wind forecast-based model predictive control [70] are also used to smooth power fluctuations. Syed et al. [31] also proposed an algorithm that establishes power reference level for injecting fluctuation-free power into grid; however, a static power reference level takes into account neither the forecasts nor the forecast errors and thus can be relied upon only with ideal forecasts. In addition, the algorithm proposed does not allow any real time communication with the grid operator. The method proposed by Javier et al. [68] is only applicable to windfarm and does not offer any communication and forecast-based control. Although the systems proposed by Islam et al. [69] and Khalid et al. [70] have forecast-based controls to smooth out power fluctuations, they do not offer communication and forecast-based energy management and control.

The literature also suggests multiple solutions for energy-related issues. Barote and Marinescu [71] proposed BESS-based energy management and control (EMC) for real power balance and power quality control in isolated areas to improve WE power supply reliability. Tewari and Mohan [72] reported peak shaving by shifting WE through BESS for integration into grid. Bunker and Weaver [73] reported the optimal control of grid-tied wind assisted by BESS. Dali et al. [74]

proposed EMC to ensure control and energy supply by BESS. Shajari and Pour [75] reported reduction of BESS size based on complimentary PV and WE assisted by BESS; while Sebastián and Alzola [76] reported on the use of EMC with fossil fuel generator (FFG) to bridge the supply and demand gap. However, all of these proposed systems [71 – 75] are based on conventional EMC (CEMC), the passive EMC that does not include wind forecasts into its decision making process, and often cause surplus curtailment and supply and demand balance issues. In addition to having these two characteristics, the system proposed by Sebastián and Alzola [76] results in environmental pollution and high operational and maintenance costs. Furthermore, the systems proposed by Shajari and Pour [75] and Sebastián and Alzola [76] require higher capital investments due to complimentary PV and FFG, respectively.

Khalid and Savkin used model predictive control to control BESS placed near wind farms to either smooth the combined power output [77] or control grid frequency [78]. However, as reported by Sharma and colleagues [79], neither [77] nor [78] considered electrical dynamics, BESS size, and state-of-charge constraints explicitly. Qi et al. [80] proposed model predictive control supervisory control for optimal management and operation of standalone hybrid PV-Wind with BESS, but with load shedding. None of the systems proposed by Khalid and Savkin [77, 78], and Qi et al. [80] provided RE curtailment and Day-ahead-commitment (DAC), E_{DAC}, delivery integrated solution. Parisio et al. [81] and Marinelli et al. [82] reported predictive EMC for a grid-tied PV-Wind hybrid system with BESS to balance day ahead committed supply of RE into grid using BESS on hourly basis. However, they overlooked curtailment and real-time (RT) communication with grid operator and thus their proposed system does not provide any solutions to the issues faced by the modern grid operators as highlighted above [67]. Therefore, this work considers this for the third application of PEMC.

1.2 OBJECTIVES

Integration of RE systems into conventional grid require solutions that can maintain real time energy balance with high power quality and service reliability while ensuring optimal coordination among all components of the RE system. RE systems, whether PV or wind, require EMC to make control decisions and manage operations. Both PV and wind RE systems suffer the same intermittency issues. Survey of literature in general and detailed analyses of the reported references and associated issues outlined earlier, reveal that the main cause of all related problems is variability and unpredictability of RE resources coupled with the passive CEMC and limited BESS storage size.

This work proposes predictive EMC (PEMC), a forecast-based EMC technique, over a defined horizon (24h) to minimize impacts of intermittency through predictive control decisions and energy management of the RE-BESS. The proposed PEMC technique focuses on collection of forecasted RE resources and load (or commitments) data over 24h horizon and performs PEMC not only to minimize the negative impacts of intermittency, but also to successfully put intermittency to work. The proposed PEMC technique consists of algorithms and optimization formulations to predictively perform EMC of RE (PV or Wind) plus BESS. PEMC predictively makes control decisions and manages RE system operations, to minimize RE curtailment and optimize resources, based on the present and future (forecasted) demands and future RE potential estimated from RE resources (wind speed or solar irradiance). The proposed PEMC techniques: 1) use RE predictively (instead of operating on the mercy of weather), 2) minimize curtailment (thus maximizing RE proportions), 3) minimize supply and demand balance issues, 4) optimally exploit BESS potential, 5) compensate for forecast errors, and 6) maximize savings (or revenue).

Proposed PEMC technique and optimization formulation are applied and validated in the following three different scenarios:

- PV – BESS system connected to grid for time-of-use (TOU) cost reduction
- PV – BESS system connected to weak grid with periodic load shedding
- WE – BESS system connected to grid for day-ahead-commitment (DAC) delivery, smoother power injection and gird support

The proposed PEMC algorithms and optimization are modelled, simulated and validated in Matlab/Simulink R2015a with MOSEK V7.0 optimization toolbox used for mixed integer optimization. Models were run using Windows 8.1 Pro, 64bit operating system, Intel^R Core™ i5-4300U CPU @ 1.90GHz - 2.50GHz.

The objectives of this work are to propose PEMC techniques that predictively:

1) minimize RE curtailment/waste leading to higher RE proportions both locally and into grid
2) minimize supply and demand balance issues leading to lower loss of load
3) exploit BESS potential while minimizing unnecessary charging from grid
4) minimize power fluctuations leading to rather smoother power injection into grid
5) minimize forecast errors impact

The by-products of the objectives identified above are:

1) minimum power import from grid leading to higher savings
2) minimum loss of load locally through predictive energy assurance
3) improved service reliability of a weak grid through increased RE proportions into grid
4) operational support for grid through on-request power adjustment/control
5) management of BESS leading to BESS use beyond storage size
6) day-ahead-committed energy delivery assurance while minimizing curtailment, leading to increased revenue

1.3 OUTLINE

In this chapter RE systems and their associated issues due to RE resources intermittency were introduced. CEMC systems were discussed and inefficiencies were listed. Research objectives were identified and the associated benefits were highlighted.

The rest of the thesis is organized as:

Chapter 2: PEMC of PV – BESS System for Time of Use Cost

Chapter 3: PEMC of PV – BESS System for Load Shedding

Chapter 4: PEMCC of Wind – BESS

Chapter 5: General Discussion and Conclusions

CHAPTER 2

PEMC of PV– BESS for Time of Use Cost

2.1 INTRODUCTION

This chapter focuses on PEMC technique for minimizing consumption from electrical network, especially during peak hours when electricity prices are high (1st scenario). Such approach not only reduces the energy cost for consumers, but also enhances energy security through local supply and storage in case of grid failure, prevents blackouts/brownouts by reducing demands on grids in peak-demand periods, and provides cushion against future grid supplied electricity price hikes (approximately 5% per year).

Ontario TOU tariff structure is used in this study, with two peak seasons, summer and winter [83], to show the effectiveness of the proposed scheme. The rest of the chapter is organized in the following sections: (2.2) Tariff Structure, (2.3) System, (2.4) Predictive Optimization, (2.5) Results and Discussion, and (2.6) Conclusions. PV [84] and load forecasting [85, 86], and PV and/or BEES size/cost optimization [37, 38] are outside the scope of this work.

2.2 TARIFF STRUCTURE

Ontario Energy Board offers two tariff structures, TOU and Tiered, with majority of the customers using TOU. Table 2.1 shows the TOU tariff structure for Ontario [83]. In this table red represents winter schedule, while blue represents summer schedule. Summer (May/1st-Oct/31st) has one and winter (Nov/1st-Apr/31st) has two on-peak periods in a day while the reverse is true for mid-peaks. The total yearly consumption cost (YCC) of a facility is given by equation (2.1):

$$YCC = \sum_{i=1}^{8760} C_i \, P_g \mathrm{t} \tag{2.1}$$

where C_i is hourly cost, P_g is grid power consumed by the facility and t is time in hours.

Excluding the weekends and holidays, there are two-hundred and fifty weekdays in each year. Therefore, there are 1500 on-peak and 1500 mid-peak hours in each year. Modifying (2.1) to reflect this based on TOU structure gives us:

$$YCC = C_p \sum_{p=1}^{1500} P_g \mathrm{t} + C_m \sum_{m=1}^{1500} P_g \mathrm{t} + C_o \sum_{o=1}^{5760} P_g \mathrm{t} \tag{2.2}$$

where C_p is hourly peak, C_m is hourly mid-peak, C_o is hourly off-peak cost.

Table 2.1: Ontario TOU (2013)

Peak	Time	$/kWh
On	11AM-5PM, 7AM-11AM & 5PM-7PM	0.129
Mid	7AM-11AM & 5PM-7PM, 11AM-5PM	0.109
Off	7PM-7AM, 7PM-7AM	0.072

In a tiered tariff structure, a higher rate is applied when the electricity usage exceeds a predefined limit. Tiered tariff structure for residential customers (RC) and non-residential customers (NRC) is presented in Table 2.2 [83]. Red represents consumption limits during winter, and blue represents consumption limits during summer for RC. For NRC, in black, consumption limit is the same for all seasons.

Still there are customers that buy electricity from electricity retailers for a price negotiated for a fixed period of time. While TOU and tiered tariff structure account for global adjustment charges, contractual customers must pay the global adjustment charges, billed per kWh, on top of the negotiated price. Global adjustment charges could be more than twice the contracted per kWh price; therefore, the net price/kWh could exceed the on-peak price.

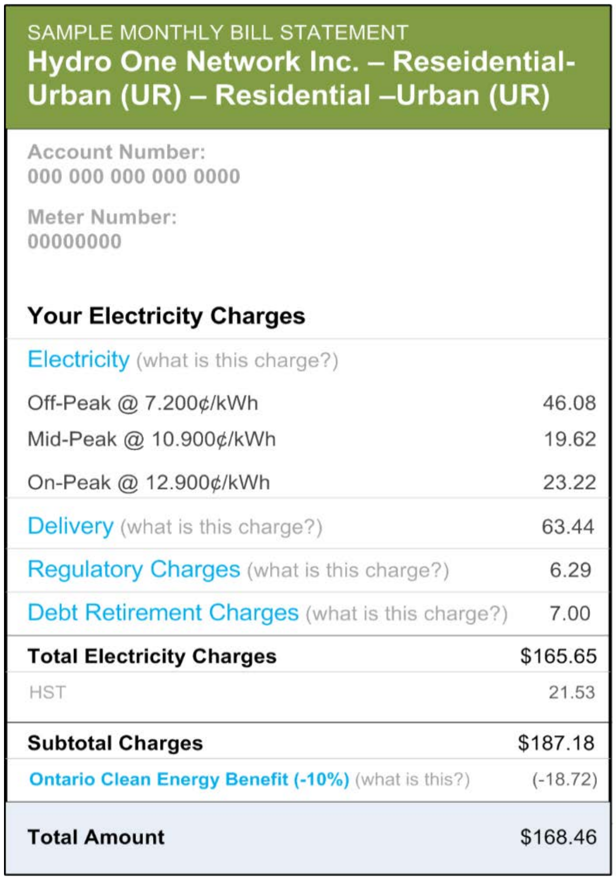
Table 2.2: Ontario tiered tariff structure

Consumer	Consumption	$/kWh
RC/NRC	≤600 kWh, ≤1000 kWh, ≤750 kWh	0.083
RC/NRC	>600 kWh, >1000 kWh, >750 kWh	0.097

PV-integrated BESS system applications might be justified based on TOU, tiered tariff structure or contractual per kWh prices offered by the utility companies. However, insight into tariff structures with delivery, regulatory, debt retirement costs and harmonized sales tax (HST), establishes investment justification beyond doubt. For example, Fig. 2.1 shows a sample monthly bill [83] for consumption of 1000 kWh/month with 18%, 18% and 64% of consumption during on-peak, mid-peak and off-peak periods, respectively. Delivery charges are 71.35% and the payable amount is 180 – 190% (real payment adjustment, R_{PA}=1.8 – 1.9) instead of 100% of the actual kWh used, proving that the actual off-peak, mid-peak and on-peak prices are much higher than the prices shown in Table 2.1. Therefore, minimizing consumption through-PV integrated BESS system is beneficial even for mid-peak and off-peak periods.

2.3 SYSTEM

A cost-effective and reliable solution to minimize the cost of electricity requires proper technology, system optimal sizing (not the focus of this work; interested readers are referred to [37, 38]) and components procurement based on the area, load profile and the prevailing tariff structure. However, PV technology is one of the best candidates since it requires no fuel, involves no moving parts, does not pollute the environment, is cheap and its price continues to decline. In addition, routine maintenance of PV technology does not require a high level of technical skills and expertise. Toronto, Ontario, has great PV potential (Table 2.3) [87].


SAMPLE MONTHLY BILL STATEMENT

Hydro One Network Inc. – Reseidential-Urban (UR) – Residential –Urban (UR)

Account Number:
000 000 000 000 0000

Meter Number:
00000000

Your Electricity Charges

Electricity (what is this charge?)	
Off-Peak @ 7.200¢/kWh	46.08
Mid-Peak @ 10.900¢/kWh	19.62
On-Peak @ 12.900¢/kWh	23.22
Delivery (what is this charge?)	63.44
Regulatory Charges (what is this charge?)	6.29
Debt Retirement Charges (what is this charge?)	7.00
Total Electricity Charges	$165.65
HST	21.53
Subtotal Charges	$187.18
Ontario Clean Energy Benefit (-10%) (what is this?)	(-18.72)
Total Amount	$168.46

Fig. 2.1: Sample monthly bill [83] used for R_{PA} calculations

BESS provides safe and efficient operation that does not depend on topography or geology. BESS requires minimum to no maintenance, has no moving parts and is scalable. Furthermore, its price is continuously dropping. Therefore, it is considered the key energy storage solution on a small scale (<MW), though it has also been employed on large scale (>MW). Zinc Hybrid Cathode (Znyth) technology [88] BESS was selected due to its low cost ($160/kWh), low maintenance requirements, high energy density, high number of cycles (10,000), high depth of discharge (DOD) (up to 100%), and a round trip efficiency of 75%.

Fig. 2.2 shows the load profile of a facility in greater Toronto area on two representative days, one in summer and another in winter. The facility's consumption was measured in 15-minute intervals for 24 hours. Fig. 2.2 shows that the lowest demand was less than 5 kW and the highest demand was 43 kW. The total connected/peak load was 50 kW. The facility's peak load was 50 kW (P_{dp}) with 1500/year total on-peak hours (hr_{pk}). Thus, the maximum energy/year (E_{EN}) that could be avoided from grid during peak-hours equals to 75 MWh given by equation (2.3).

Table 2.3: Toronto PV potential (South facing) [87]

Month	KWh/m^2(0^o tilt)	KWh/m^2(30^o tilt)
January	52.1	80.9
February	63.8	83.4
March	111.6	130.8
April	147	156
May	166.2	159.9
June	174.6	161.5
July	191.6	180.4
August	163.7	165.9
September	117	130.6
October	77.5	100.7
November	38.4	47.8
December	36.6	54.3
Year	1340.1	1452.1

$$E_{EN} = hr_{pk}P_{pd} \qquad (2.3)$$

where P_{dp} is peak load, hr_{pk} is on-peak hours, and E_{EN} is energy per year from grid.

Using equation (2.4) with DOD=100%, d=250 days, η=75% (BESS round trip efficiency), the amount of energy to be stored by BESS (E_{BESS}) on weekdays equals to 400 kWh/day.

$$E_{BESS} = (E_{EN}/d)/(DOD * \eta) = 400 \text{ kWh/day} \qquad (2.4)$$

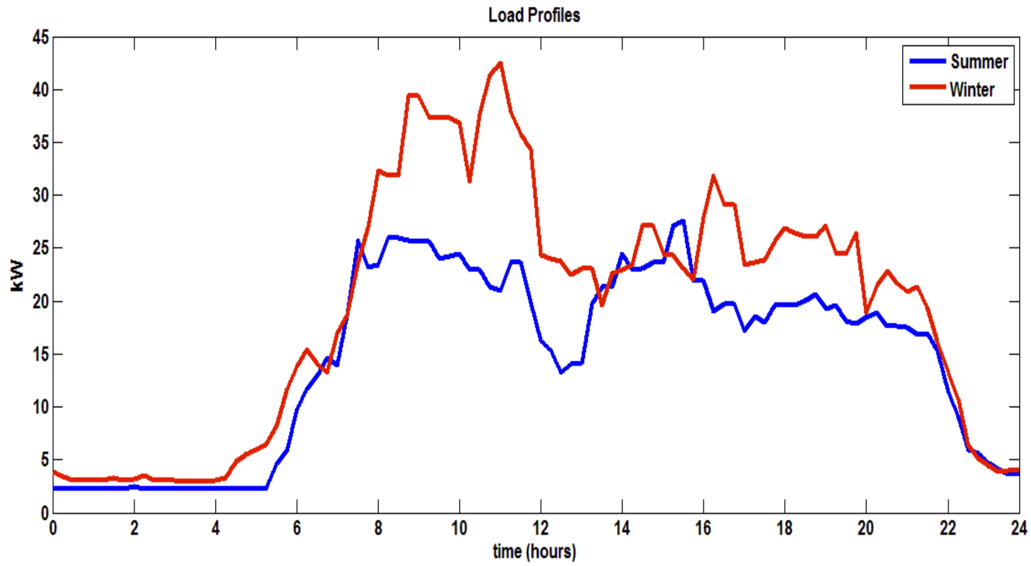


Fig. 2.2: Load profiles of a facility in Toronto area during a summer (blue) and winter (red) day

The average peak sun hours (PSH) per day for Toronto area is given by equation (2.5). PV potential of the south facing system at tilt angle of 20° and Azimuth of 1° equals to 1413.8 kWh/m^2 [87], which gives PSH=3.87.

$$PSH = PV_{year}/365 = 3.87 \tag{2.5}$$

where PV_{year} is yearly PV energy (1413.8 kWh/m^2).

A system size (PV_{size}) equals to approximately 100 kW sized for average PSH=3.87 and costs $185k (at $1.85/W engineered, procured and installed).

$$PV_{size} = E_{BESS}/PSH \ = 100 \text{ kW} \tag{2.6}$$

The expected energy yield of such system is given by equation (2.7) and equals to 115MWh/year with a derate factor (D_f) of 80% to account for loss, soiling, etc.

$$E_{PV} = D_f PV_{year} PV_{size} = 115\text{MWh/year} \tag{2.7}$$

Without BESS size optimization and based on the current prices ($160/kWh) [88] for battery storage, BESS would require a capital investment of $64k. This scheme will result in a yearly savings of approximately $17,608 (using equation (2.8)) and investment recovery in less than 4 years with 250 charge/discharge cycles, if on-peak consumption alone is reduced. Due to the extra 15MWh available, after on-peak cost reduction is achieved, mid-peak consumption reduction is possible without adding any charge/discharge cycles, directly through PV.

$$\$_{Save} = R_{PA} R_{on-pk} E_{EN} \tag{2.8}$$

where $R_{on\text{-}pk}$ is on-peak rate ($0.129) and R_{PA} is real payment adjustment (1.8 – 1.9).

Fig. 2.3 shows the PV output of a system in Toronto, Ontario, for a representative day in summer (July 11, 2013 chosen since July is usually the hottest month in Ontario) and winter (December 23rd, 2013, the 3rd shortest day of the year; the 1st and 2nd shortest days were weekends).

PV output values are measured at 15-minute intervals. Summer day operation starts at 6 AM and ends at 9:30 PM with its peak (78.5 kW) around 2 PM. Winter day operation starts at 8:15 and ends at 5:15 pm with a peak of 53.5 kW at 12:45 PM. The total energy delivered on December 23rd was 567.275 kWh, greater than 400 kWh needed to offset on-peak usage.

2.4 PREDICITVE OPTIMIZATION

Predictive optimization was performed to predicatively optimize the cost by avoiding energy consumption from the grid during 24h time period. It was primarily focused on high price on-peak periods, using PV, load demand and weather forecasts in addition to BESS status.

Predictive optimization over 24h horizon with 15-minute time intervals (Δt) was performed to optimize a day ahead operation. Predictive optimization was repeated every Δt to define a new 24h optimal schedule when new load power demand forecasted (PDF), forecasted PV potential (PVF) and forecasted weather were available. Therefore, for any single Δt, the control signal u(k) contained 96 predictions of each PVF, PBF and forecasted grid power PGF. Although predictive optimization was performed every Δt over a prediction horizon, N=24h/Δt=96, only the first Δt optimally predicted schedule was applied for that Δt. At the end of Δt, predictive optimization was repeated to define a new 96-Δt optimal schedule and again only the first Δt optimal reference, PBF* (power command for BESS), was applied across BESS for charge/discharge. Thus, prediction horizon was moved/receded in future (or time) by steps of Δt. The PVF, PDF, weather forecast, and a programmable TOU for 96-Δt's (24h) are taken into account during every Δt to optimize and predict PBF*. Predictive optimization predicts PBF* every Δt treating all the predictions constant until the next Δt.

The proposed cost function, where the difference between forecasted load demand (P_{DF}(k)) and forecasted PV output (P_{PVF}(k)) is minimized over prediction horizon, N, through forecasted power from/to BESS (P_{BF}(k)) to reduce consumption/cost from grid subject to (2.10) – (2.14) is given by:

Minimize: $J(U,k) = \sum_{k=0}^{N-1} C_E\,(k) P_{gF}(k)\Delta\mathrm{t}$ (2.9)

$$P_{gF}(k) = P_{DF}(k) - P_{PVF}(k) - P_{BF}(k) \quad (2.10)$$

$$E_{BF}(k) = E_{BF}(k-1) + \eta P_{BF}(k)\Delta\mathrm{t} \quad (2.11)$$

$$-P_{B-max} < P_{BF}(k) < +P_{B-max} \quad (2.12)$$

$$E_{B-min} < E_{BF}(k) < E_{B-max} \quad (2.13)$$

$$0 < P_{gF}(k) < P_U \tag{2.14}$$

Equation (2.10) ensures real power balance, where $P_{gF}(k)$, $P_{DF}(k)$, $P_{PVF}(k)$, $P_{BF}(k)$ are grid, demand, PV and battery forecasted powers at k. Equation (2.11) gives BESS energy at time k $E_{BF}(k)$, that equals past interval BESS energy $E_{BF}(k-1)$ and change in BESS energy during Δt ($P_{BF}(k)\Delta t$) with efficiency $\eta=1/\eta_c$ for charging and $\eta=\eta_d$ for discharging. $P_{B\text{-}max}$ and $-P_{B\text{-}max}$ in (2.12) are charge/discharge maximum limits in any interval Δt. $E_{B\text{-}min}$ and $E_{B\text{-}max}$ in (2.13) are the lower and upper limits on BESS energy defined by maximum level of status of charge and maximum (or safe) level of depth of discharge allowed. Equation (2.14) prohibits the system power supply into grid at any time k by $P_{gF}(k) > 0$ and power from grid limited by f P_U=100kW due to connection capacity limits.

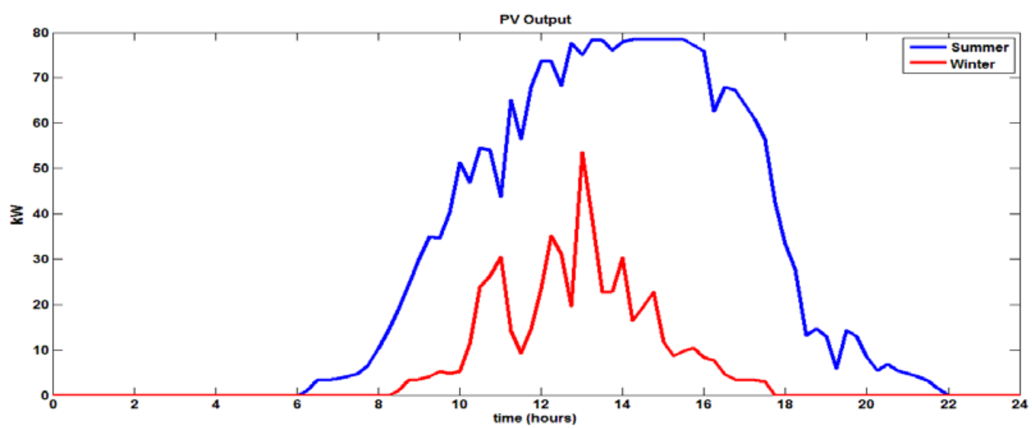


Fig. 2.3: PV production in a summer (blue) and winter (red) day

Fig. 2.4. shows the proposed predictive optimization algorithm (based on Fig. 1.1). All forecasts, system/components bounds and constraints are supplied. TOU tariff based on the season, day of the week and time of the day is determined and BESS status is measured. One of the 3 paths is appropriately followed.

Off-peak path allows for optimal charge or discharge of BESS, based on the present BESS status, load demand, PV, and TOU and the predicted future BESS, load demand, PV and TOU over N predictions horizon. If BESS energy at present time k, $E_{BF}(k)$, or $E_{BF}(k)$ plus E_{PVF} (k to k+n) (forecasted PV cumulative energy from k to k+n) is greater than or equal to the energy that would be required for the present plus forecasted load demand during on-peak period ($E_{BPDF@OP}$) plus mid-peak period, then allow BESS to discharge and supply for the load demand during this Δt. On the other hand, if the aforementioned conditions are not met, then do nothing, that is do not allow BESS to discharge or let PV supply for the load demand. Predictive optimization continues to perform the optimization in identical manner, either discharging or doing nothing during off-peak period. At 00:00 AM predictive optimization assesses 24h predicted potential of PV, predicted load demand, weather forecast and present BESS to decide whether BESS should be charged by the grid or not and programs TOU accordingly. This decision is re-evaluated every Δt (or k) to rectify the previous (k-1) decision if the situation has changed due to changes in the forecasts.

Alternatively, if it is mid-peak and $E_{BF}(k)$, or $E_{BF}(k)$ plus E_{PVF} (k to k+n) is greater than or equal to the energy that would be required for the present plus forecasted load demand during on-peak period ($E_{BPDF@OP}$), then advance BESS energy usage for Δt by programming TOU and performing predictive optimization. Otherwise do not allow the discharge and reserve the stored energy for on-peak period. Similar to off-peak, predictive optimization revisits the process and defines a new optimization schedule over full prediction horizon every Δt; however, it only applies the first optimal PBF* if conditions are met for supply of local energy (BESS and/or PV) to the load demand in that Δt.

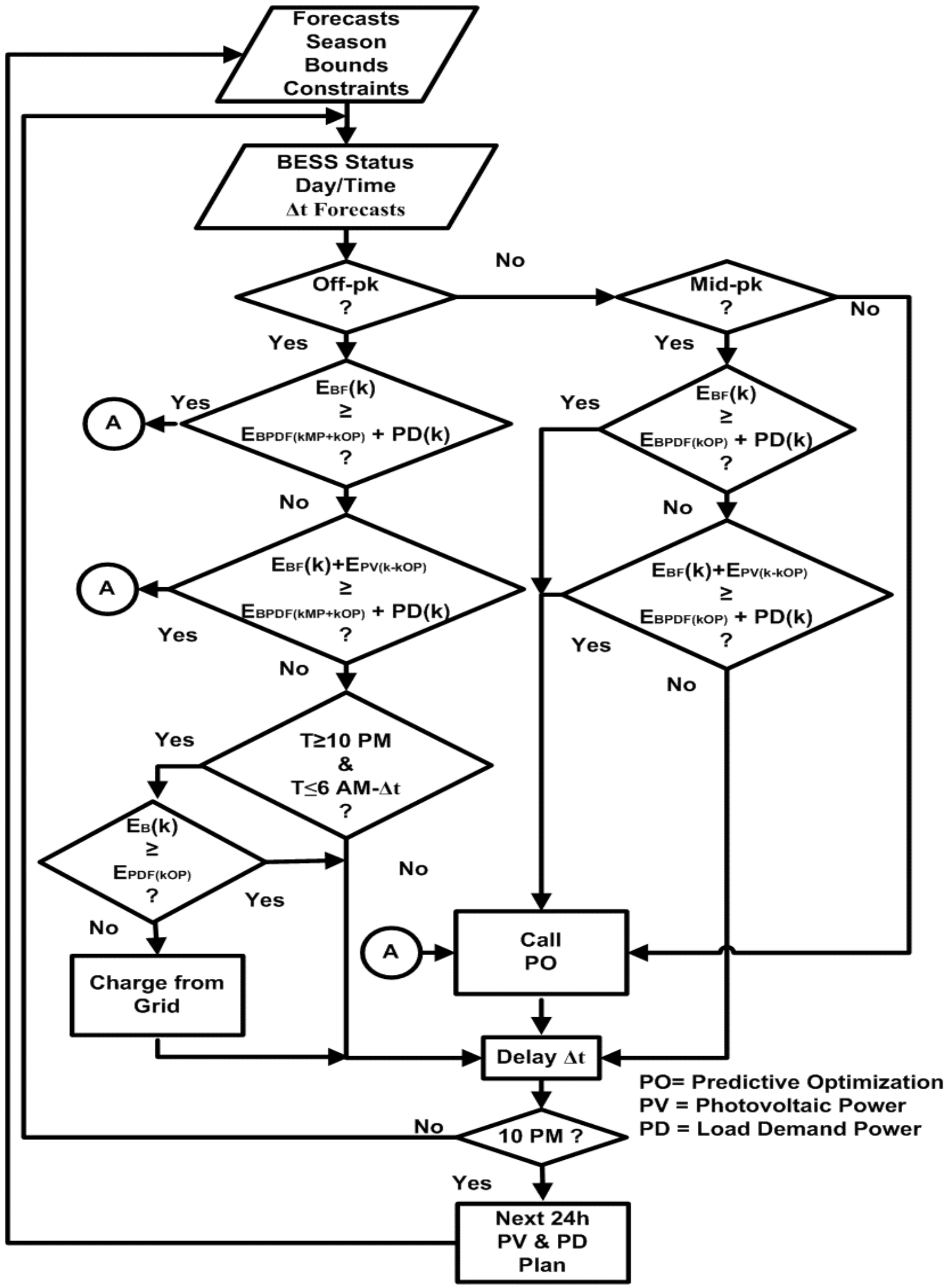


Fig. 2.4: The proposed predictive optimization algorithm

Finally, during on-peak period all resources are used to minimize consumption from the grid and a similar way in off- and mid-peak periods by programming TOU. Predictive optimization repeats optimization process over prediction horizon every Δt with the newly available forecasted values of parameters and BESS status by receding (or moving) into future. Predictive optimization ensures that optimization is established sequentially, from on-peak to off-peak successively, with on-peak cost reduction being the main focus. Advancement (or delay) of BESS energy is the key feature of the proposed predictive optimization algorithm that allows lower PV curtailment and efficient energy storage use based on the present and predicted future system status, thus increasing PV penetration and lowering the cost.

It is important to note that errors of up to 4% in magnitude may be associated with the forecasts on 24h basis [84]. Thus load demand and/or PV will not remain fixed for the duration of Δt and system could operate in one of three modes: local energy (BESS and/or PV) greater than the load demand (mode-1), local energy equal to the load demand (mode-2), and local energy less than the load demand (mode-3). However, there is no need for separate local control systems since: 1) the system is grid-tied and operates in grid following mode, thus voltage stability or frequency regulation is not an issue; 2) real power balance associated with mode-3 may be maintained by the grid through supplying the difference; 3) mode-1, extra energy allocated simply does not get used as the amount of local energy supplied to the load is defined by the load demand itself in addition to predictive optimization; 4) predictive optimization inherent feedback mechanism; that is, predictive optimization cycle repeats every Δt with the newly available forecasts and BESS status rectifying any prediction error; and 5) error per Δt is small (0.042% or 1/96th of 4%).

2.5 RESULTS AND DISCUSSION

To validate the effectiveness of the proposed methodology, the actual load profile data for a typical day in summer and in winter (Fig. 2.2) and the real PV output data (Fig. 2.3) for sites in greater Toronto area were used. Matlab was used for predictive optimization implementation.

Fig. 2.5 and 2.6 show the 24h operation of the PV integrated BESS system with the proposed predictive optimization without BESS advancement (energy use advanced or delayed in time). Fig. 2.5 shows a typical winter day, where two peaks of the day are from 7 to 11 AM and 5 to 7 PM, one mid-peak from 11AM to 5PM and one off-peak from 7 PM to 7 AM (Table 2.1). The unit of the horizontal axis is Δt with 96 units/day. Only the peak demand period is targeted without BESS advancement to reduce consumption from grid; therefore, the grid supplies power (PG, red) during off-peak from 00:00 AM (0^{th} unit) to 7AM (28^{th} unit). During the first peak from 28^{th}-44^{th} unit, the load power demand (PD, blue) is matched by PV power (PV, green) and BESS power (PB, cyan) together (28^{th}-38^{th}), or PV alone (39^{th}-44^{th}). When PV supply is greater than the load demand (39^{th}-56^{th}), PV supplies for load from 44^{th}-56^{th} unit during mid-peak and charges BESS (negative PB) from 39^{th}-55^{th} unit. At 55^{th} unit load is supplied again by PV alone; however, PV becomes less than PD after this point and thus the load is supplied by PV and PG until 65^{th} and by PG from 65^{th}-68^{th} unit. During the 2^{nd} peak, from 68^{th}-76^{th}, the load is supplied by PB alone. Finally, PG supplies for the last off-peak period (76^{th}-96^{th}) of the 24h period. PVGB (PV+PG+PB, yellow) shows the load demand being matched by optimal combination of PV, PG and PB for the whole day. This 24h optimal schedule is renewed every Δt until the end of the day. The cycle is repeated every day with 96-Δt intervals. If required, BESS is charged from grid based on BESS status at present time (k), the next day forecasted PV potential until on-peak start time and forecasted load demand during on-peak time. BESS charge from grid is allowed only during off-peak periods from 10 PM to 6 AM and for forecasted load demand during on-peak time only.

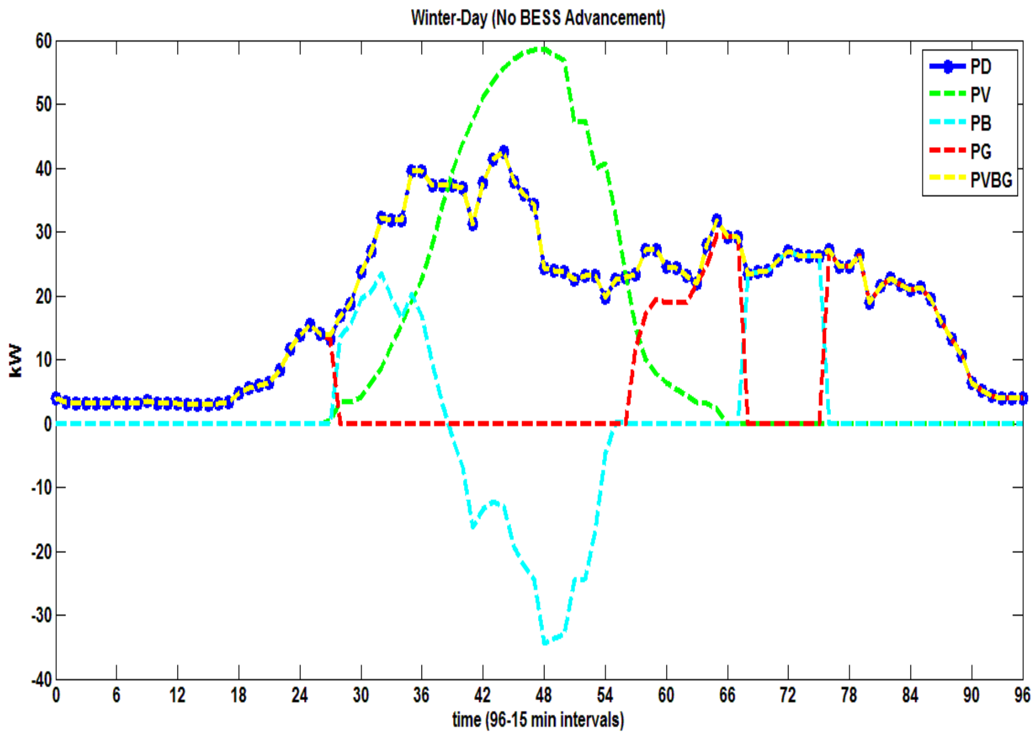


Fig. 2.5: Typical winter day operation (CEMC)

Fig. 2.6 shows 24h operation for a typical day in summer, when there is one peak per day from 11AM to 5 PM, two mid-peaks from 7 AM to 11 AM and 5 PM to 7 PM and one off-peak from 7 PM to 7 AM (Table 2.1). Again, only the peak demand is targeted without BESS advancement. PG supplies during off-peak periods (0-28th & 76th-96th). When PV is less than PD (before 32nd and after 69th unit), PG and PV supply for PD. PV alone supplies for PD when equal to or greater than PD, i.e., from 33rd-69th unit.

The followings can be observed by detailed analysis of Figures 2.5 and 2.6: 1) BESS was underutilized from 55th-68th unit on a winter day, 2) the same is true for the two mid-peaks on a summer day, 3) PV potential was very high on this selected day; however, it was underutilized and was wasted due to the facts that PD was small and BESS was full. Therefore, an intelligent predictive optimization with BESS advancement is required to better exploit the resources.

Fig. 2.7 repeats the same operation as in Fig. 2.5 with mid-peak BESS advancement included in the predictive optimization. By simple comparison it is evident that there is no PG during mid-peak and on-peak periods resulting in additional savings. This is made possible by the predictive part of the proposed predictive optimization algorithm where forecasted load demand and PV in conjunction with BESS status, over prediction horizon, are manipulated to optimize and advance utilization of the resources.

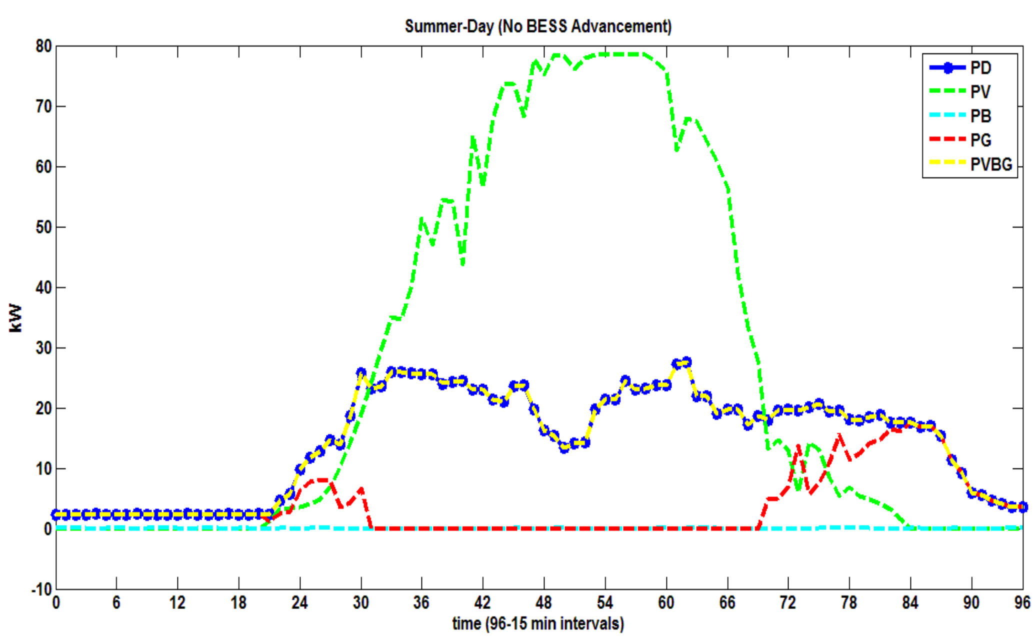


Fig. 2.6: Typical summer day operation (CEMC)

Fig. 2.8 repeats the same operation as in Fig. 2.6 with the proposed predictive optimization, optimizing and advancing operations for all peaks throughout the day. BESS energy utilization is advanced to reduce consumption from grid and thus the cost. On this specific day no PG was purchased at all, instead a combination of PV and BESS was used to supply for the load resulting in zero cost of energy from the grid for the whole day.

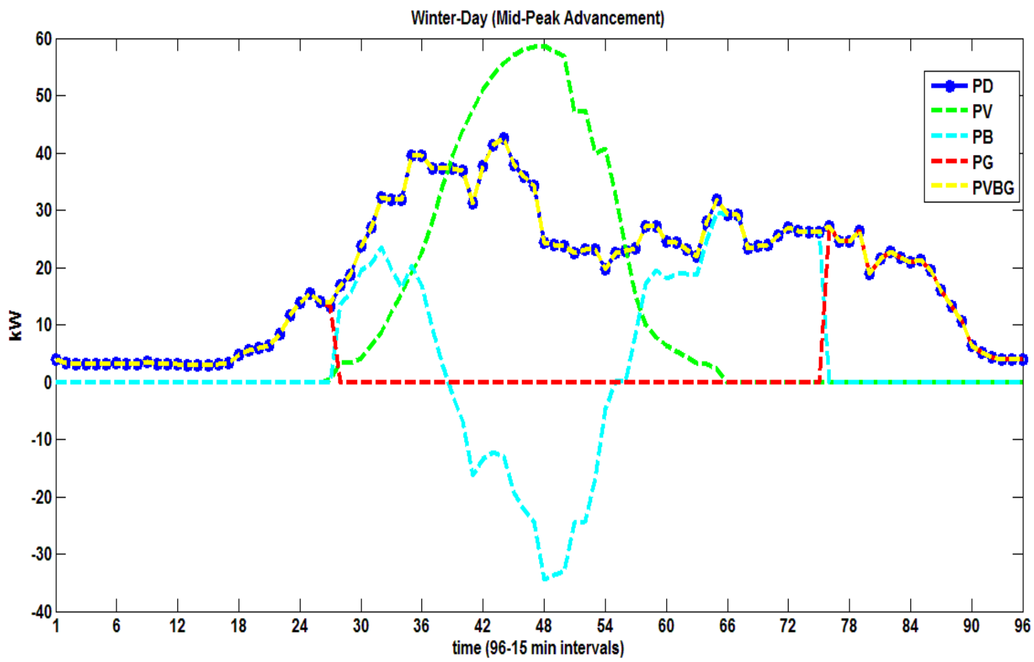


Fig. 2.7: Winter day operation with BESS advancement (PEMC)

If BESS is charged from grid (case-1), then 100 MWh (75MWh/0.75, as η=75%) is required to supply for 75 MWh yearly on-peak load demand (2). This will cost \$13104.00 (100 MWh x off-peak price x R_{PA}) to charge, instead of \$17608.50 (100 MWh x η x on-peak price x R_{PA}); a saving of \$4504.50 per year. If PV – BESS with predictive optimization without BESS advancement (Figures 2.5 and 2.6) is used, the system will efficiently optimize for on-peak periods and savings will improve; however, this approach would result in curtailment of PV energy and thus energy would be wasted. Thus, 100 MWh out of 115 MWh produced by PV system will be used during on-peak periods; a saving of $17608.50. Finally, if PV – BESS with predictive optimization with BESS advancement (Figures 2.7 and 2.8) is used, BESS energy usage can be advanced or delayed in time, based on the forecasts, to define the best possible operational strategy. This will allow optimization at present and for future beyond on-peak periods, targeting mid-peak and even off-peak when possible based on the resources at present and potentials in future. Thus, all the 115 MWh produced by PV system is used; 100 MWh in on-peak periods (a saving of $17608.50) and 15 MWh in mid-peak (an additional saving of $2231.77 (15 MWh x η x mid-peak price x R_{PA})).

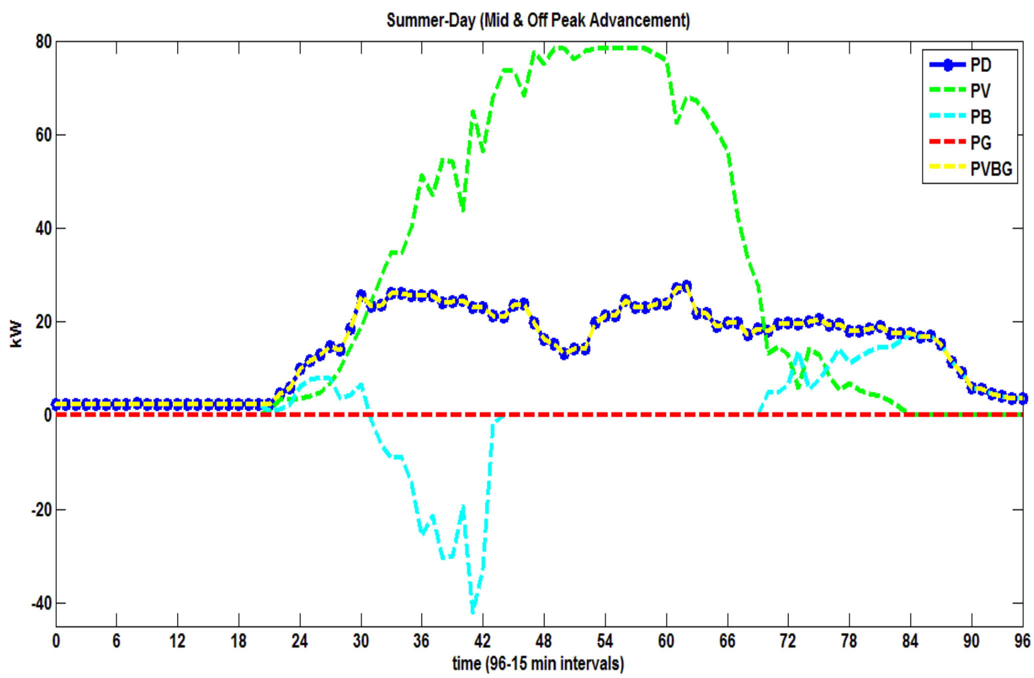


Fig. 2.8: Summer day operation with BESS advancement (all peaks)

2.6 CONCLUSIONS

In this chapter we presented PEMC of PV – BESS. The proposed scheme plans and allocates resources at present and for future based on the present and futuristic potential of multiple resources. PEMC repeats every 15 minutes, compensating for forecast errors and correcting for prediction errors, defining new optimal operational strategy for available resources to match the load demand for 15-min interval while reducing consumption from the grid in on-peak period. PEMC enables BESS advancement (or delay) to significantly decrease curtailment and increase PV energy use to reduce consumption even further in mid- and off-peak periods. Results show that the proposed PEMC with forecasted PV, load demand, and predicatively estimated BESS status can reduce the cost of electricity by reducing consumption from the grid. In addition, PEMC enhances energy security through local energy resources, protects consumer against continuous grid supply price hikes, and supports grid by reducing load demand during peak demand periods.

The focus of this work has been on PEMC of PV – BESS, not its financial viability. Thus financial analysis of the proposed scheme is trivial. Even if the proposed scheme does not have any immediate universal application, it may have grand implications in the future. Based on the indicative prices already quoted in this work, designing, procurement and installation of a 100kW PV system with 40kWh BESS would cost $249k (185k + 64k). Now with 2016 TOU rates for the said utility, savings of $28.256k using (2.8) considering on-peak and mid-peak periods savings in the first year is possible. The average saving per kWh is 0.2457 ($28.256k/115MWh). With the price hike of 5% and production deprecation of 0.5% per year, payback time is estimated to be less than 8 years, as tabulated in Table 2.4 and shown in Fig. 2.9.

Table 2.4: PV – BESS Financial Analysis over 20 years

Year	$$ Flow
1	-$ 220,744.50
2	-$ 191,217.50
3	-$ 160,361.79
4	-$ 128,117.57
5	-$ 94,422.36
6	-$ 59,210.87
7	-$ 22,414.86
8	$ 16,036.97
9	$ 56,219.14
10	$ 98,209.50
11	$ 142,089.43
12	$ 187,943.95
13	$ 235,861.93
14	$ 285,936.22
15	$ 338,263.85
16	$ 392,946.22
17	$ 450,089.30
18	$ 509,803.82
19	$ 572,205.49
20	$ 637,415.24

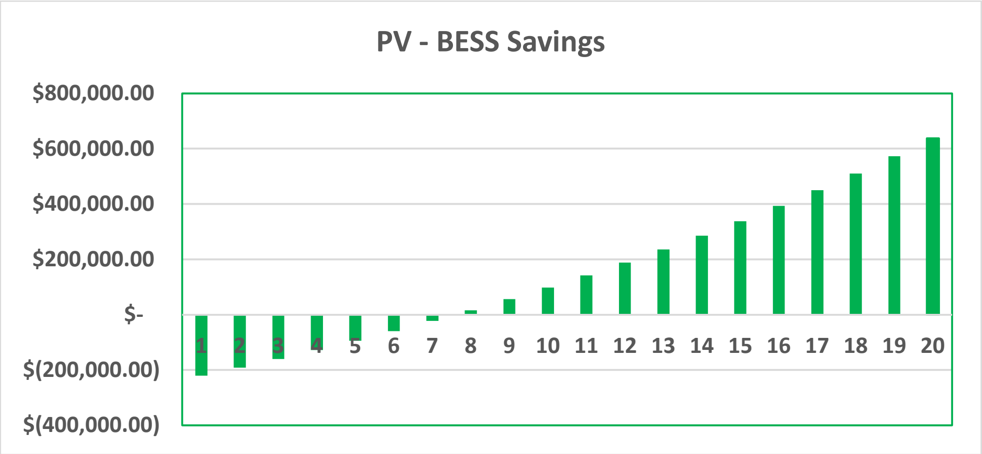


Fig. 2.9: PV – BESS savings: cash flow over 20 years

Finally, Table 2.5 presents advantages of PEMC through comparative analysis of the proposed PEMC based PV – BESS with BESS and CEMC based PV – BESS schemes.

Table 2.5: Comparative Analysis

	BESS	PV – BESS CEMC	PV – BESS PEMC
Curtailment	N/A	Yes	Minimum
Surplus at k	N/A	Store	Store
Shortage at k	N/A	Supply	Supply
Surplus at k + n	N/A	No Action	Supply
Shortage at k + n	N/A	No Action	Store
Grid Charge	Yes	Un-planned	Planned
Optimization	No	k	k & k + n
Utilization	Sub-optimal	Sub-optimal	Optimal
Savings	Sub-optimal	Sub-optimal	Optimal
Energy Security	Grid	Yes	Yes
Environment Friendly	No	Yes	Yes

CHAPTER 3

PEMC of PV System for Load Shedding

3.1 INTRODUCTION

This chapter focuses on PEMC of PV – BESS microgrid to minimize curtailment and thus increase PV proportions in a weak grid with planned periodic load shedding to increase its energy supply reliability (2^{nd} scenario). Specifically, PEMC achieves: a) energy supply assurance in period, b) increased PV energy for consumers, c) increased grid reliability through higher PV proportions into grid due to lower curtailment, and d) consumer cost savings through lower energy consumption from grid. The aforementioned are collectively called 4-goals in this chapter. The proposed PEMC is based on forecasted PV potential and load profile with utility periodic load shedding schedule over 24 hours (h) horizon in the future. Water And Power Development Authority (WAPDA) Pakistan, a weak grid with periodic load shedding, is used as an example [89] to show the effectiveness of the proposed PEMC. PV and load forecasting, and BESS size/cost optimization are outside the scope of this work; the interested readers are referred to [84-86, 37, 38].

PV – BESS microgrid has been selected since: 1) PV technology is the ideal candidate for these types of applications 2) Islamabad, Pakistan, has great PV potential with a global horizontal irradiation of 1860 kWh/m^2 at zero degree tilt and global incident at collector plane of 2140 kWh/m^2 per year at 30^o tilt due south system [87], 3) BESS provides a safe and efficient operation that does not depend on topography or geology, 4) PV – BESS requires minimum to no maintenance, has no moving parts and is scalable, 5) the price of PV – BESS is continuously dropping, and 6) BESS is considered the key energy storage solution on a small scale (<MW), although it has also been employed on large scales (>MW). The Zinc Hybrid Cathode technology BESS was selected due to its low cost, low maintenance requirements, high energy density, high number of cycles, high DOD, and high efficiency [88].

The rest of the chapter is organized in the following sections: (3.2) Utility load shading profile, (3.3) Grid-tied PV – BESS system, (3.4) PEMC, (3.5) PEMC formulation and algorithm, (3.6) Simulation, results, and discussion, and (3.7) Conclusions.

3.2 UTILITY LOAD SHEDDING PROFILE

Fifty percent of Pakistan has access to electricity. The total installed capacity is 20GW with a shortage of 6GW [89]. Six GW translates into approximately 5-6 hours of load shedding per day on average when weekends and public holidays are taken into account. Load shedding durations are usually longer in villages (rural areas) and shorter in cities (urban areas), with cities having an average load shedding of 2 to 4 hours per day. Hence, residential, commercial and industrial sectors have relied on FFG to continue to function. However, due to the higher cost of fossil fuel, promising PV potential [87], incentive for PV technologies, and recent Net-Metering rules [90], Pakistan is poised for installing PV and PV – BESS at residential, commercial and industrial levels.

Introduction of recent Net-Metering rules, with kWh (unit) price equal for injection and retrieval, allows for surplus energy to be injected into grid and retrieved when PV – BESS is insufficient for local load. The majority of PV systems connected to grid are PV – BESS microgrid type and continue to operate in standalone mode when grid fails. However, storage and usage for load shedding period is focused, without any injection into and retrieval from the grid. This approach ensures energy supply during load shedding period; however, it hinders full exploitation of PV resources and often results in PV energy curtailment. Hence, the existing PV – BESS microgrid based on conventional schemes are inefficiently operated with wastage of surplus PV energy due to curtailment, which is accepted as norm. PV – BESS microgrid can be better exploited and PV share can be increased in the grid if PEMC based on PV potential and load forecast with periodic load shedding schedule over the next 24h is used. Therefore, this work considers WAPDA as a case of weak grid with periodic load shedding of 3 hours/day from 11 AM to 2 PM, 7 days a week, 365 days a year to show the effectiveness of PEMC for grid-tied PV – BESS microgrid. The main focus of PEMC is to achieve the 4-goals outlined in the introduction without compromising consumer energy supply reliability.

3.3 GRID-TIED PV – BESS SYSTEM

Equation (3.1) can be used to size BESS, where, E_{BESS} is BESS energy, E_D is load shedding period demand, DOD is depth of discharge, and η is BESS round trip efficiency.

$$E_{BESS} = E_D/(DOD * \eta) \tag{3.1}$$

The required BESS equals to 40kWh/day to ensure energy supply during 3h load shedding period (11AM-2PM), for a facility with a peak load E_D of 30kWh (10kW x 3h load shedding period), BESS DOD of 80% and η of 95%. DOD of 80% is chosen to extend the life of BESS battery. The required PV system size (PV_{size}) is estimated by equation (3.2) and is approximately 7kW. The PSH is given by equation (3.3) and equals to 5.86 for Islamabad, Pakistan, with irradiance (G) of 2140 kWh/m^2.

$$PV_{size} = E_{BESS}/PSH \tag{3.2}$$

$$PSH = G/365 = 5.86 \tag{3.3}$$

However, an oversized PV system is required to ensure sufficient supply in all conditions including: 1) winter with shorter periods of sun during a day ($PSH_{Dec} \leq 1/3$ - $3/4$ of PSH_{Jun}) [87], 2) cloudy/rainy days, and 3) with PV systems 20% loss (or derate factor (D_f) of 80%) to account for losses due to light, soiling, electrical, etc.). Using equation (3.4) the PV system is resized to be 12kW. BESS size can also be increased, if autonomy or backup for more than one load shedding period is required.

$$PV_{size} = (E_{BESS}/PSH)/(\eta * D_f) \tag{3.4}$$

The PV yield of such a system is given by equation (3.5) and equals to 20.54 MWh/year. However, the maximum energy required during load shedding period per year is 11.6MWh (40kWh/day x 365 days' x 0.8), leading to a surplus of around 8.86MWh of energy per year. With the conventional schemes this surplus is simply wasted. Although the system can save some capital costs if the size of the PV system is reduced, this approach degrades energy supply reliability, especially in winter and on cloudy/rainy days.

$$E_{PV} = D_f * G * PV_{size} \tag{3.5}$$

Fig. 3.1 shows the hourly PV output of a system in Islamabad, Pakistan, for a representative day in summer (June 21st, the longest day) and winter (December 21st, the shortest day) [87], interpolated at 15-minute intervals with 96 samples in 24h period with the help of a program written in Matlab. Summer day (red) operation starts at 5AM and ends at 7:20PM, while winter day (green) operation starts at 7:10AM and ends at 5:00PM. The red (or plus signs) and green (or circles) lines represent horizontal global incident irradiation in summer (HgiS) and winter (HgiW), respectively. Similarly, cyan (triangle) and blue (circle) lines represent horizontal diffused irradiation for the respective days in summer (HdiS) and winter (HdiW), respectively. Both summer and winter days' peak at 11:30AM with global horizontal irradiation of 900 and 500Wh/m^2, respectively.

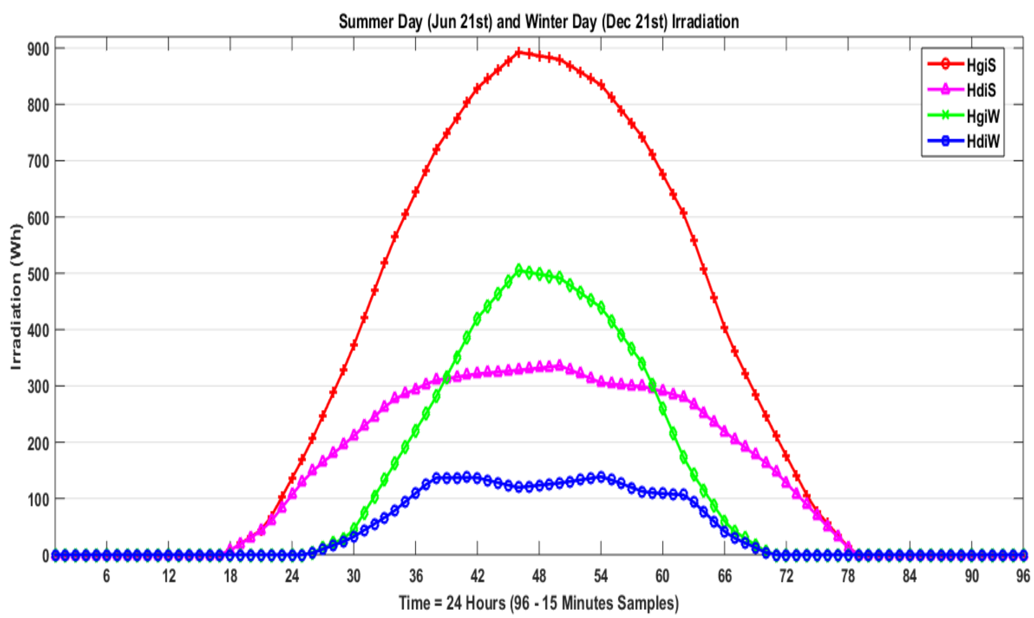


Fig. 3.1: Solar Irradiation: HgiS, HdiS, HgiW, and HdiW Interpolated at 15-minute intervals

Fig. 3.2 shows the energy production of 12kWp PV system on both summer and winter days, with a total of 47kWh on 21st of December and 61kWh on 21st of June [87], interpolated at 15-minute intervals with 96 samples in 24h using the Matlab code. Summer (Eos) and winter (Eow) days peak at 11:30AM (in this case) with 7.5 and 8kW, respectively. It is worth noting that even on the shortest day of the year, December 21st, the total energy (47kWh) is greater than 40kWh needed to ensure supply during 3h load shedding period.

3.4 PREDICTIVE ENERGY MANAGEMENT AND CONTROL

Conventional techniques inject surplus energy into grid when and if surplus PVE is available. However, conventional schemes based PV – BESS tied to weak grid with load shedding periods, resort to curtailment and cause PV energy waste, falling short of full exploitation of PV resources. Consider a conventional control scheme based PV – BESS, with BESS full and PV generation greater than the load demand at n^{th} hour during load shedding period (grid unavailable). PV surplus is evident since PV is greater than the load; however, this surplus cannot be used (BESS full, load cannot consume, and grid unavailable) and thus is curtailed and wasted. Therefore, efficient and optimal exploitation of PV resources require a control system that not only ensures energy supply reliability during load shedding periods, but also assures injection of the available surplus PV into the grid with minimal curtailment and waste during 24h including load shedding period. In addition, the control system must support grid by enhancing its energy supply reliability through higher PV proportions, and saving energy cost for consumers through higher local consumption.

Conventional schemes are designed and employed with passive algorithms, where solutions are sought when operational uncertainty appears. In other words, a solution is sought, control variables are modified and operation is adjusted after the negative impacts of the already occurred error have been detected. Thus control is based on feeding back the sensed error(s) to modify the operational criteria to control the error and minimize its negative effects. PEMC on the other hand, based on the forecasted vital information of weather and RE resources with predictive load profile, could potentially foresee the futuristic error and: 1) predict the system's resources (both currently available resources and the ones required in the future), 2) predict the system's present and future operational conditions, 3) prepare corrective actions (at present), 4) apply corrective actions to avoid anticipated futuristic error(s), and 5) minimize (or possibly eliminate) the anticipated negative impact(s) of errors. This futuristic assessment, an integral part of PEMC, with corrective actions applied before operational uncertainties arise, allow PEMC to eliminate errors or reduce their impact before they actually occur, instead of feeding sensed errors back (feedback). Thus, PEMC proactively rely on estimating future error(s), defining an operational strategy, preparing control actions and applying them before the error(s) actually occur.

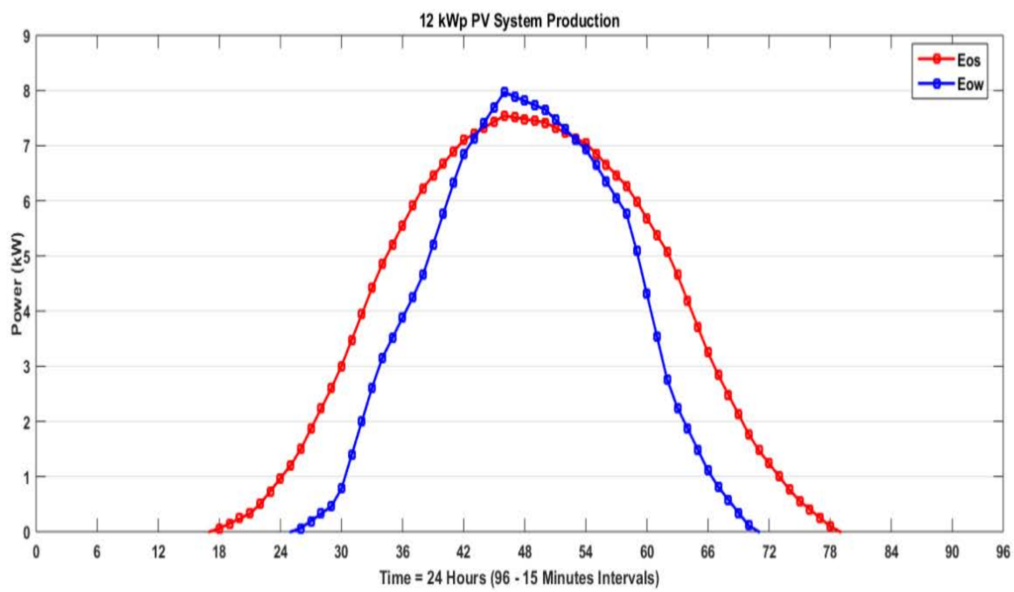


Fig. 3.2: 12kW system summer (Eos) & winter output (Eow) interpolated at 15-minute intervals

Weather and RE resources forecasts are vital for PEMC reliable implementation/operation. However, forecasts have intrinsic uncertainties; the accuracy of daily weather and PV resources forecasts is 96% and 97%, respectively [91, 92]. Thus, the proposed PEMC scheme must have a mechanism to mitigate the effects of errors in weather/PV forecasts. In addition, the PEMC requires load shedding schedule and load demand profile (historical/forecasted) to schedule/allocate resources and control PV – BESS microgrid operations.

In this work the PEMC scheme controls and optimizes PV – BESS microgrid based on predictively estimated PV potential, BESS measured and estimated future statuses, load demand profile and utility load shedding schedule, to ensure energy supply during load shedding periods with lower PV curtailment. Twenty-four hours' operation is divided into three modes of operation, as shown in Table 3.1. Mode 1 (PEMC Mode), from 6AM to 11AM and 2PM to 10PM, is a grid-tied mode. The system operates in grid following grid-tied mode (grid available), with PV and/or BESS supply for load and/or inject power into grid based on forecasts/profiles/BESS-status. This mode also allows power from grid, if required, in case PV and/or BESS cannot supply for the load. Mode 2 (load shedding Mode) is a standalone mode, from 11AM to 2PM. PV and/or BESS operates in grid forming standalone mode (grid unavailable) and supply for load. Mode 3 (No-PEMC Mode) is again a grid-tied mode from 10PM to 6AM. PV and/or grid supplies for load. If required, BESS is charged from grid based on forecasts/profiles. However, a charge from grid is rarely required since PEMC can foresee over 24h in the future and proactively manage BESS to avoid unnecessary grid charge and the associated cost.

For control purposes, a day is divided into 96 intervals, 15 minutes (Δt) each. In other words, a control decision made is valid only for Δt, and would require reassessment of all the necessary variables (forecasts/profiles/BESS-status) to make a new decision for the next Δt. This 96 decisions a day PEMC scheme allows PEMC to reassess the present and future weather and PV resources, BESS status, load demand and load shedding profiles to make a new decision for the next Δt (future) every 15 minutes. Operation and control decisions made at t=k (present) are applied to the system at =k+1 (the next interval, future) and the system is allowed to operate for 15 minutes, while new operation and control decisions are prepared based on the updated 24h data available to be applied at t=k+2. Thus, PEMC uses15-minute intervals to step into future, with the 24h forecasts being updated every Δt to make decisions at t=k to be applied at t=k+1. Revision and renewal of decisions every Δt over 24h horizon based on the updated and progressively available 24h forecasts/profiles/BESS-status profoundly reduce uncertainties associated with all types of forecasts/profiles/BESS-status, minimize RE curtailment (waste), ensure reliable supply in load shedding period, and ensure consumer cost savings. Decision renewal, every Δt, also provides a self-correction mechanism for the PEMC.

Table 3.1: Modes of Operation over 24 hours

Mode	Time	Description
1	6-11AM & 2-10PM	PEMC periods: grid-tied mode, PEMC is performed to achieve 4-goals
2	11AM-2PM	load shedding periods: Standalone mode, No PEMC is performed and all available resources are used to supply for load demand.
3	10PM-6AM	NPEMC Periods: No PEMC is performed and BESS is charged from grid if required.

3.5 PEMC FORMULATION AND ALGORITHM

The proposed PEMC runs PV – BESS microgrid in three distinct modes (No-PEMC (NPEMC/Mode-3), PEMC/Mode-1 and load shedding/Mode-2) over 24h horizon, each with its own resources and unique requirements. Therefore, based on the mode of operation and its respective operational environment, different mode-specific operational policies are required and proposed. In NPEMC/Mode-3 (10PM – 6AM) BESS energy is restricted and never used to ensure customer comfort with energy supply assurance in futuristic load shedding period. Load is primarily supplied by grid and plus PV if available. BESS charge from grid is also allowed in this mode, if required. In load shedding/Mode-2 (11Am – 2PM) grid is unavailable; therefore, load is supplied by PV and/or BESS and surplus is stored across BESS, if there is room. Similarly, if PV is less than the load, then the required energy is supplied by BESS. No BESS energy is supplied if BESS energy is less than the load demand. In PEMC/Mode-1 (6AM-11AM & 2PM-10PM) PV, BESS, load and grid all interact with each other. Thus, the available resources change moving from mode to mode and every mode requires its own distinct formulation and operational philosophy. Hence, the proposed PEMC is a two-part solution: proposed predictive optimization and proposed predictive algorithm.

A) PEMC: Proposed Predictive Optimization

Main focus is to ensure there is neither loss of load due to energy shortage nor curtailment due to energy surplus during load shedding period. Therefore, PEMC must ensure energy for load and room for surplus in BESS during load shedding period. This requires optimal balance between the two conflicting BESS supply and storage capacities during futuristic load shedding period. PEMC predictive optimization, therefore, requires resources and demands forecasted data and status for optimal distribution and utilization of resources over 24h horizon. Utilizing such data, predictive optimization can avoid violating any constraints/bounds associated with the grid, BESS, etc., and ensure optimal balance between energy shortage and surplus. Note that lack of both energy supply shortage and energy curtailment is the focus of futuristic load shedding – Mode-2; however, PEMC is run in Mode-1 (before load shedding period). In other words, optimal operational decisions made in the Mode-1 ensure meeting targets in the futuristic load shedding – Mode-2.

The objective function of the proposed predictive optimization (3.6) is minimized during load shedding period over 24h prediction horizon, subjected to (3.8) - (3.13). $P_{CF}(k)$ is forecasted curtailed (or shortage) power for interval Δt given by equation (3.7), and is the difference between the forecasted PV ($P_{PVF}(k)$) and the load ($P_{DF}(k)$).

Minimize: $$J(U,k) = \sum_{k=LSi}^{LSf} P_{CF}(k)\Delta t \qquad (3.6)$$

Where,

$$P_{CF}(k) = P_{PVF}(k) - P_{DF}(k) \qquad (3.7)$$

Subject to (3.8) – (3.13) in PEMC period:

$$P_{gF}(k) + P_{BF}(k) + P_{PVF}(k) - P_{DF}(k) = 0 \qquad (3.8)$$

$$E_{BF}(k) = E_{BF}(k-1) + \eta P_{BF}(k)\Delta t \qquad (3.9)$$

$$-10kW = -P_{B-max} < P_{BF}(k) < +P_{B-max} = 10kW \qquad (3.10)$$

$$0 < P_{BF}(k) < P_{CF}(k) \qquad (3.11)$$

$$E_{B-min} = 8kWh = 0.2E_{B-max} < E_{BF}(k) < E_{B-max} = 40kWh \qquad (3.12)$$

$$-P_L = -10\text{kW} < P_{gF}(k) < +P_U = +10\text{kW} \qquad (3.13)$$

$$E_{BF}(k) < \sum_{LSi}^{LSf} E_{DF-LS} \quad (3.14)$$

$$E_{BF}(k) + \sum_{j=24}^{88} E_{PVF} \geq \sum_{LSi}^{LSf} E_{DF-LS} + P_{DF}(k)\Delta t \quad (3.15)$$

Thus equation (3.6), representing load shedding – Mode-2 (LS_i to LS_f for 3h or 12Δt) operational resources, is used to minimize forecasted curtailment or shortage of power by running predictive optimization during PEMC – Mode-1. In other words, the difference between forecasted load $P_{DF}(k)$ and forecasted PV output $P_{PVF}(k)$ during futuristic load shedding period is minimized through predicted power from/to BESS ($P_{BF}(k)$) at present (during PEMC – Mode-1), given by equation (3.8). Equation (3.9) gives $E_{BF}(k)$, BESS energy at time k, through the past interval BESS energy $E_{BF}(k-1)$ and $\eta P_{BF}(k)\Delta t$. $P_{BF}(k)\Delta t$ gives BESS energy during Δt with efficiency $\eta=1/\eta_c$ for charging and $\eta=\eta_d$ for discharging. In general, P_{B-max} and $-P_{B-max}$ in equation (3.10) are charge/discharge maximum limits in any interval, Δt. However, equation (3.11) modifies equation (3.10) during PEMC period. Thus equation (3.11) restricts $P_{BF}(k)$ to 0 on low side to prohibit BESS charging, and to the difference of forecasted PV and load ($P_{CF}(k)$) to limit discharge to the surplus (probable curtailed power) in the load shedding period. E_{B-min} and E_{B-max} in equation (3.12) are the lower and upper limits of energy storage in BESS defined by the maximum level of status of charge and maximum (or safe) level of DOD allowed (80%). Equation (3.13) imposes upper (P_U=10kW) and lower (P_L=-10kW) limits power to/from grid during any interval k. Finally, equations (314) and (3.15) check for charging and curtailment conditions. Equation (3.14) determines if BESS energy at k is less than the forecasted load shedding period required energy and equation (3.15) examines whether BESS energy at k plus forecasted load shedding period PV energy is greater than forecasted load shedding period required plus load demand energy at k to avoid curtailment.

B) PEMC: Proposed Predictive Algorithm

To minimize curtailment or shortage during forthcoming load shedding/Mode-2, PEMC is run during PEMC/Mode-1 when grid is available. In other words, futuristic forecasted surplus in load shedding/Mode-2 is injected into grid during PEMC/Mode-1. Thus PEMC: 1) increases PV proportions into grid, 2) stores PV energy across grid for later use at no cost to customer (Net-Metering rules), 3) creates room across BESS for surplus, and 4) minimizes PV curtailment in the forthcoming load shedding/Mode-2. These goals have to be achieved without compromising energy supply during load shedding/Mode-2 through appropriate selection of one of the 3 paths of proposed predictive algorithm, as shown in Fig. 3.3.

NPEMC/Mode-3 path (dark blue, Fig. 3.3) is chosen and the system is operated in grid-tied mode from 10PM to 6AM. No predictive optimization is performed in NPEMC/Mode-3 and the load is supplied by grid and/or PV (if available). At 00:00AM the predictive algorithm assesses 24h forecasts, PV potential, load demand, and present BESS status, to decide whether BESS should be charged by grid. If required, BESS is charged from grid to ensure supply in the upcoming load shedding period. To avoid BESS unnecessary charging and limit the energy in BESS to the required energy in load shedding periods, charging decision is re-evaluated every Δt (k) interval, with successively available new / updated forecasts / profiles / BESS-status.

Load shedding/Mode-2 path (red, Fig. 3.3) is followed from 11AM to 2PM unconditionally, utilizing all available resources (PV and BESS) to ensure supply for load operating in grid forming standalone mode. No PEMC is performed, since grid is not available. The difference between PV and load is either stored or supplied by BESS. If BESS is full and PV is greater than the load, then the surplus gets curtailed and wasted. Similarly, if BESS available energy is less than what is required by load, then partial or full load is shed as required.

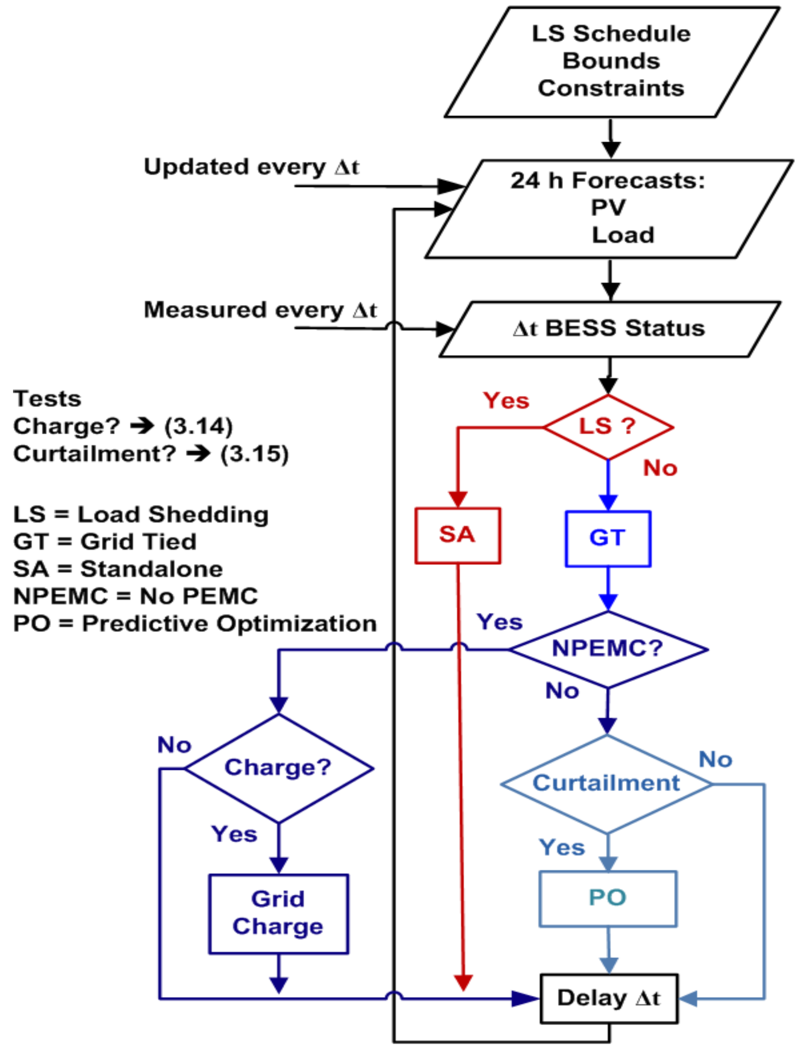


Fig. 3.3: Proposed PEMC with predictive algorithm and predictive optimization

Finally, the PEMC/Mode-1 path (light blue, Fig. 3.3) is chosen and the system is operated in grid-tied mode (6AM to 11AM and 2PM to 10PM). PEMC predicatively optimizes and controls PV – BESS microgrid, using forecasts / profiles / BESS-status over 24h horizon. PEMC predictive algorithm assesses resources and operational scenario at t=k (present) and passes on all the variables (forecasts / profiles / BESS-status) to predictive optimization. Predictive optimization runs optimization cycle and prepares control decisions to be applied at t=k+1 focusing on 4-goals over 24h horizon.

For every k, PEMC is performed over a complete prediction horizon, N=1 to 96; however, only the first PEMC schedule is applied for the next Δt. PEMC is repeated to define a new 96-Δt PEMC schedule and again only the first Δt optimal reference, PBF* (reference command for BESS), is applied across BESS for charge/discharge or no operation. The forecasted P_{PVF} and P_{PDF}, load shedding schedule and BESS status for all 96-Δt's are taken into account during every Δt to predict PBF* for t=k+1. PEMC treats all the forecasts / profiles / BESS-status as constant, until the next Δt, to predict PBF*.

The actual values of load and/or PV can vary from forecasted ones due to error(s) associated with PV forecasts and load profiles and this variation can negatively affect operation and system reliability. Operation in NPEMC/Mode-3 and PEMC/Mode-1 is grid-tied, thus forecast / profile errors have no noticeable impact since grid is available and can support the system in maintaining its reliability. However, in load shedding/Mode-2, PV – BESS microgrid is operated in standalone mode with no grid available to support. Therefore, the PV – BESS microgrid may operate with local energy (BESS and/or PV) which is greater than, equal to, or less than the load. However, no additional control mechanism is required since: 1) predictive optimization plus predictive algorithm are run in grid-tied modes only, 2) predictive optimization inherent feedback mechanism (due to decisions revision every Δt with the newly available forecasts / profiles / BESS-status) keeps prediction errors to minimum, and 3) error per Δt is small (1/96th of 4%, i.e., 0.042%). A safety margin, equal to probable error, can be added to the algorithm, if required. That is, BESS can be ensured to keep an extra 5% energy on top of what is required by the load during load shedding/Mode-2 to avoid supply shortage in the load shedding period. However, this will cause some curtailment and thus has not been implemented in this work. The following few cases outline achievement of 4-goals during PEMC/Mode-1:

Case 1: a) BESS at t=k+1(next Δt) is full, b) PV potential at t=k+1is zero, and c) PV potential during future load shedding period (k+n) is promising (≥load shedding period load demand)

⇨ PEMC supplies energy from BESS to load and/or grid during the next Δt

Case 2: a) BESS energy estimated at t=k+1 is low, b) PV potential at t=k+1is promising, and c) PV potential during load shedding period (k+n) is promising (≥load shedding period load demand)

⇨ PEMC supplies PV energy to load and/or grid during the next Δt

Case 3: a) BESS energy estimated at t=k+1is low, b) PV potential at t=k+1 is promising, and c) PV potential during load shedding period (k+n) is not promising (< load shedding period load demand)

⇨ PEMC stores PV energy in BESS and allows the grid to supply load during the next Δt

Analysis of the cases 1 to 3, in PEMC/Mode-1, reveals the following:

1) **Case 1**: BESS predictively discharges to supply energy into grid (since grid is available now) and/or load based on forecasts / profiles / BESS-status over 24h horizon to: i) create room across BESS for upcoming PV surplus and thus avoid PV curtailment during load shedding period, ii) increase PV proportions across grid, iii) save consumer energy cost since energy stored across grid can later be retrieved for no additional cost, and iv) increase

grid reliability by using the otherwise wasted surplus energy to support weak grid consumers (4-goals).

2) **Case 2**: BESS predictively discharges to supply energy into grid (since grid is available now) and/or load based on forecasts / profiles / BESS-status over 24h horizon to: i) increase PV proportion across grid, ii) save consumer energy cost, iii) use the otherwise wasted energy for supporting weak grid increasing its reliability (3-goals).
3) **Case 3**: BESS predictively inhibits discharge based on forecasts / profiles / BESS-status over 24h horizon to avoid probable energy supply shortage during load shedding period.

Collectively, PEMC over 24h horizon with predictive algorithm and predictive optimization, makes energy management and control decisions to achieve the defined 4-goals.

3.6 RESULTS AND DISCUSSION

The effectiveness of the proposed PEMC with predictive optimization and predictive algorithm was tested with a 12kWp PV, 40kWh BESS, Δt interpolated energy output in winter (Fig. 3.2), and the load profile is presented in Fig. 3.4.

Fig. 3.5 shows the 24-hour operation of the PV integrated BESS system with the conventional scheme. The horizontal axis has a unit of Δt with 96 units/day. PV and BESS are used with load shedding period load demand focus in SA mode only. Therefore, grid alone supplies power (PG, red) for load (PD, blue) for 21 hours except during load shedding period (11AM to 2PM), where PV (PV, green) and/or BESS (PB, cyan) are used to operate the system. If PV is greater than PD, then the surplus PV energy is stored across BESS if room available, otherwise it is curtailed and wasted. On the other hand, when PV is less than PD, the load is supplied by BESS if BESS has the capacity; otherwise the load is shed due to supply shortage. Fig. 3.5 reveals that PV surplus goes unused and wasted from 10PM to 6AM (88^{th} to 24^{th} Unit, 8h) in NPEMC/Mode-3, from 6AM to 11AM (24^{th} to 44^{th} Unit, 5h) and 2PM to 10PM (56^{th} to 88^{th} Unit, 7h) in PEMC/Mode-1, and from 11AM to 2PM (44^{th} to 56^{th} Unit, 3h) in load shedding/Mode-2. There is no supply shortage and load is supplied as shown by PVBG (yellow). The BESS is reserved for load shedding/Mode-2 and PV is used during load shedding period only. This scheme results in: 1) PVE surplus waste, 2) non-optimal use of BESS (BESS was not used at all during load shedding since PV was greater than PD for all 3h), 3) no support for weak grid by PV – BESS by surplus PV injection, and 4) no-way of knowing if BESS has enough energy for forthcoming load shedding period.

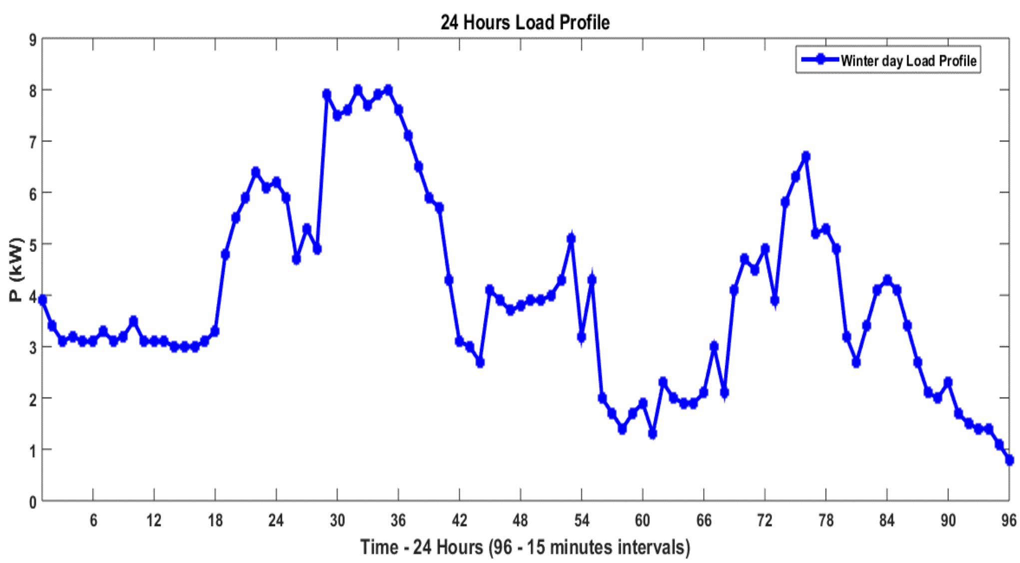


Fig. 3.4: Winter Day Load profile interpolated at 15-minute intervals

An alternative conventional scheme could be to use PV – BESS for load shedding period, and PV during other periods as well but for load only (as shown in Fig. 3.6). Therefore, in this case we see some improvement and graphs show that PV fully or partially supplies for load in coordination with PG during PEMC/Mode-1. Fig. 3.6 shows: 1) PV surplus wastage during PEMC/Mode-1 (41^{st} to 44^{th} and 56^{th} to 64^{th} unit) and load shedding/Mode-2 (44^{th} to 56^{th} unit), 2) non-optimal use of BESS (BESS was not used at all), 3) no support for weak grid (no PV – BESS surplus injection into grid), and 4) no way of knowing if BESS has energy for the upcoming load shedding period.

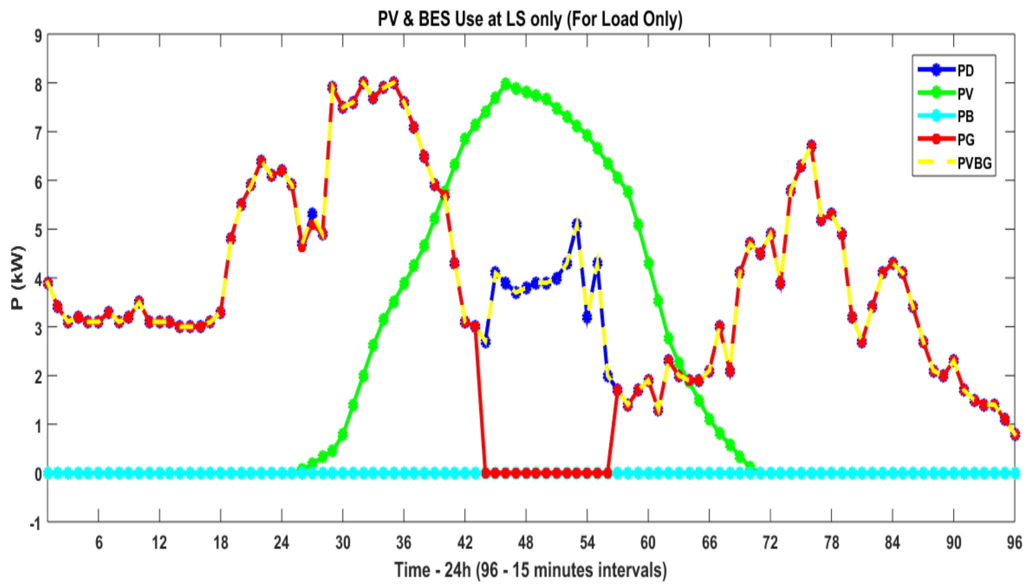


Fig. 3.5: PV & BESS use for load shedding period only (for load only, CEMC)

Fig. 3.7 uses PV – BESS for load shedding period with PV for both load demand and grid support. The figure shows: 1) PV surplus waste during load shedding period only (PV surplus was supplied to load and/or grid), 2) non-optimal use of BESS (BESS was not used at all), 3) PV supported weak grid by surplus injection (shown by negative PD), and 4) still no way of knowing BESS status for the upcoming load shedding period.

The proposed PEMC based on the proposed predictive algorithm and predictive optimization eliminates all the issues associated with schemes presented in Fig. 3.5 to 3.7. PEMC with forecasts

/ profiles / BESS-status over 24h horizon ensures optimal use of PV – BESS microgrid for all periods over 24h horizon. Fig. 3.8 shows the result of PEMC with predictive algorithm and predictive optimization over 24h horizon. The figure shows: 1) no PV surplus waste during load shedding period, 2) optimal use of BESS, 3) PV support for weak grid (shown by negative PD) through surplus PV, and 4) knowledge of BESS status for upcoming load shedding period.

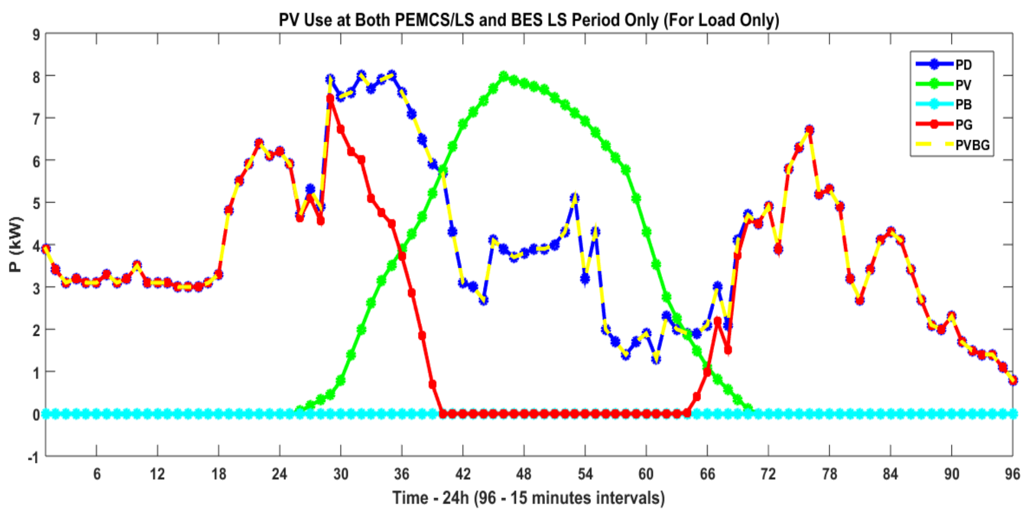


Fig. 3.6: PV use for load with BESS for load shedding period only (CEMC)

As shown in Fig. 3.8, PV supplies for load (PD) and/or grid (PG) during all periods, whenever surplus and grid are available. To eliminate waste due to curtailment during forthcoming load shedding/Mode-2, PEMC/Mode-1 predictively injects probable surplus into grid. Note that this decision lasts for Δt and the process is repeated with a new decision for the next Δt based on the updated forecasts. In other words, the portion of load shedding period forecasted PV surplus is time-shifted and used to supply for load and/or inject into grid during the next Δt in PEMC/Mode-1. Since load shedding period forecasted probable PV surplus, if any, is a futuristic surplus, BESS is used to supply PB equal to load shedding period surplus. This way load shedding period surplus (supplied by BESS in advance) is injected into grid during PEMC/Mode-1, when grid is available. This allows PEMC to not only minimize curtailment in the load shedding period, but also ensure support for weak grid through surplus PVE injection, resulting in higher PV proportions for grid. Due to rain (PV=0) and low BESS energy, supply shortage during upcoming load shedding period deem possible. However, note that PEMC runs over 24h horizon with 24h forecasts available and thus can predictively assess such situation in the upcoming load shedding period and charge BESS from grid, if required.

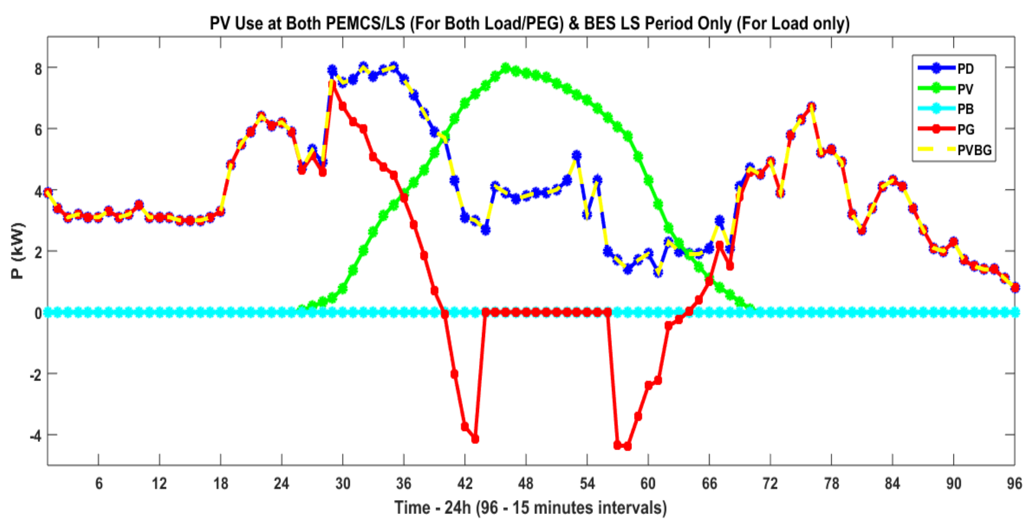


Fig. 3.7: PV use for load/grid with BESS for load shedding period only (CEMC)

Forecast errors are inevitable and can result in increased or decreased PV and/or load, and in turn cause PV surplus waste and/or supply shortage. The proposed PEMC scheme with predictive algorithm and predictive optimization, however, includes a self-correction mechanism to mitigate the impact of such errors. Fig. 3.9 shows forecast error in PEMC/Mode-1 increased PV at 32nd and 33rd units while operating in PEMC/Mode-1 (compare Fig. 3.9 with Fig. 3.8). Results show that PEMC increased injection into grid (PG) to accommodate the increased PV. Note that there was no operational change during load shedding period, therefore, PB (Cyan) supply remains unchanged. A similar pattern can be observed if PV drops below its forecasted values during PEMC period.

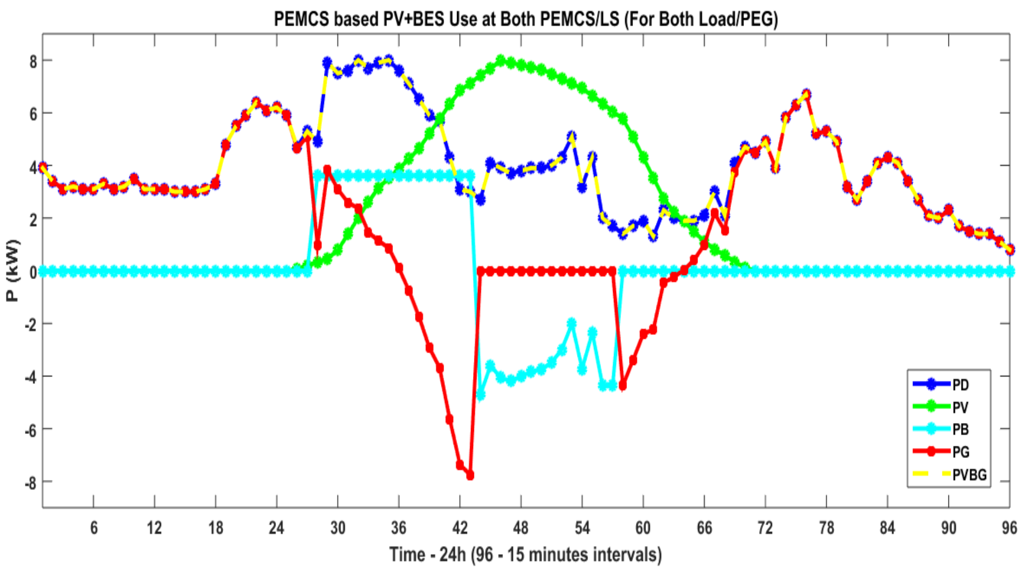


Fig. 3.8: PV – BESS use for load & grid (PEMC)

Forecast errors can also appear in the forthcoming load shedding/Mode-2 while operating in PEMC/Mode-1. Again, forecast error can increase or decrease PV (same for change in load), and in turn cause PV surplus loss and/or supply shortage. However, as pointed earlier, the proposed PEMC revises and rectifies its decision every Δt with new operational policy based on the available updated forecasts / profiles / BESS-status to adjust the operational parameters. Fig. 3.10 shows the response of PEMC to forecast error (increased PV), at 49th and 53rd units during load shedding period (compare Fig. 3.10 with Fig. 3.8 at the same time/unit). Results show that PEMC increased injection into grid (PG) to lower curtailment/waste and increase PV proportions into grid. The forecast error happens to be in the forthcoming load shedding period, not PEMC/Mode-1 period.

Thus, PB (cyan) is forced to increase injection into grid to create room for futuristic load shedding period surplus and minimize curtailment. A similar pattern can be observed if PV decreases below the forecasted values.

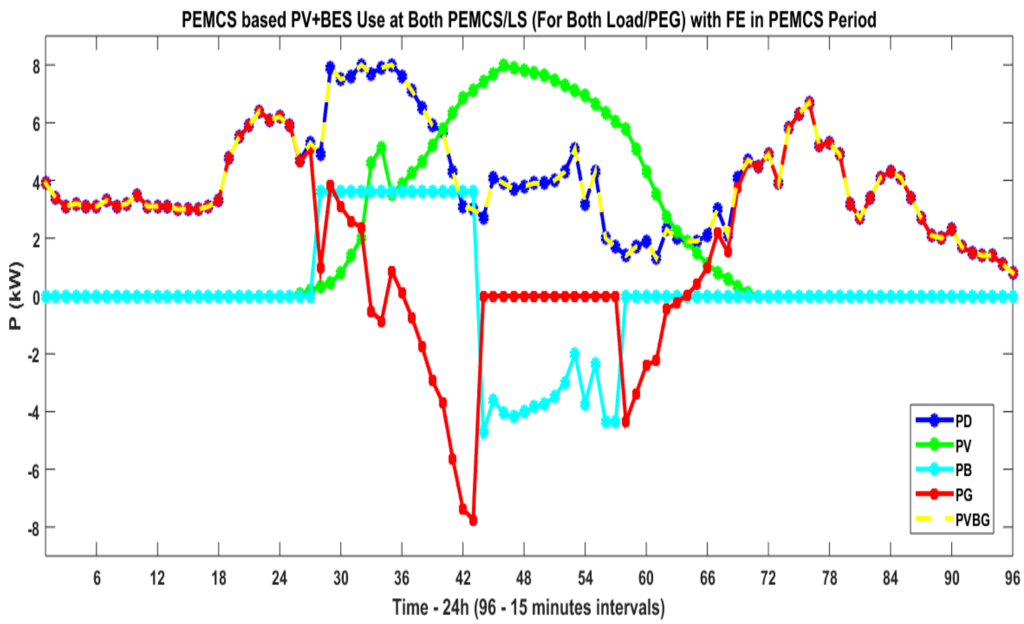


Fig. 3.9: PV – BESS use for load/grid with forecast errors in PEMC period (PEMC)

The negative impacts of forecast errors increase: 1) as we get closer to the load shedding period while operating in PEMC/Mode-1 and 2) when operating in load shedding/Mode-2. Forecast errors at (1) and (2) can cause curtailment and/or supply shortage. However, forecast error is ≤ 3% and is distributed over 24h horizon, therefore, its effects will be negligible. Recall that BESS can supply 32kWh at 80% DOD (0.8*40kWh), which is 2kWh greater than the 30kWh required during load shedding period. Therefore, even if the whole 3% forecast error happens during load shedding period, BESS will still be able to take care of it (since 3% forecast error equals to 1.41kWh on December 21st (3% of 47kWh), and 1.83kWh on June 21st (3% of 61kWh)).

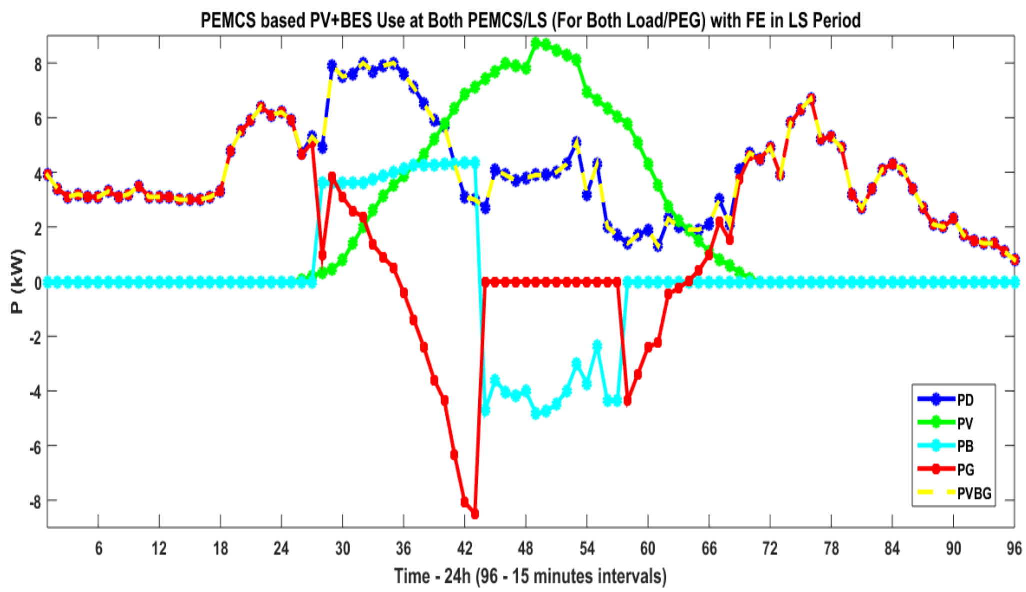


Fig. 3.10: PV – BESS use for load/grid with forecast errors in load shedding period at multiple k

3.7 CONCLUSIONS

In this chapter we presented PEMC with predictive optimization and predictive algorithm for PV – BESS microgrid. The proposed PEMC predictively optimizes and allocates resources to realize the objectives at present and in the future based on the present and futuristic forecasts / profiles / BESS-status. PEMC with proposed predictive optimization and proposed predictive algorithm follows one of the three paths to predictively define the optimal operational strategy every 15 minutes and ensure balance between the two conflicting requirements of meeting load demand and minimizing surplus curtailment. PEMC ensures: 1) energy supply for owner/customer in load shedding period, 2) minimum curtailment to i) increase PV proportions locally, ii) increase cost savings for owner/customer through lower energy consumption from grid, and iii) increase grid reliability through higher PV proportions into grid. In addition, the proposed PEMC reduces unnecessary charging of BESS from grid. Results can easily be extended to other RE technologies, such as wind.

Table 3.2 presents advantages of PEMC through comparative analysis of the proposed PEMC based PV – BESS with BESS and CEMC based PV – BESS schemes.

Table 3.2: Comparative Analysis

	BESS	PV – BESS CEMC	PV – BESS PEMC
Curtailment	N/A	Yes	Minimum
S &D issues	Yes	Yes	Minimum
Surplus at k	N/A	Store	Store
Shortage at k	N/A	Supply	Supply
Surplus at k + n	N/A	No Action	Supply
Shortage at k + n	N/A	No Action	Store
Forecast error Compensation	N/A	No	Yes
Grid Charge	Yes	Un-planned	Planned
Optimization	No	k	k & k + n
Utilization	Sub-optimal	Sub-optimal	Optimal
BESS storage limit	Capacity	Capacity	Virtual - PEMC
Savings	Sub-optimal	Sub-optimal	Optimal
Energy Security	Weak Grid	Yes	Yes
Grid Support	No	No	Yes
Environment Friendly	No	Yes	Yes

CHAPTER 4

PEMC of Wind System

4.1 INTRODUCTION

Modern grid operators require RE resources, including Wind systems, to submit a 24 to 48-hour energy output forecasts, hour by hour ahead of real-time delivery to establish their DAC of energy supply. Depending on the geographic location, installation dispersion, and the forecast method used, the typical 24h/day-ahead forecast error ranges from 12 to 25% of rated capacity [93]. However, forecast error is smaller for shorter periods [67, 93].

Therefore, this chapter focuses on PEMC plus Communication (PEMCC) of Wind – BESS connected to grid for day-ahead-commitment (DAC) delivery, smoother power injection and gird support (3rd scenario). PEMCC performs 1) forecast-based predictive power smoothing, 2) forecast-based predictive EMC, and 3) two-way communication (2WC) with the grid operator to coordinate operation. The proposed PEMCC establishes hourly energy estimates (E_{HEE}), DAC energy (E_{DAC}), and defines predictively forecasted power injection level (P_{CF}), to be tracked by PEMCC. PEMCC ensures meeting DAC with minimum power fluctuations. PEMCC minimizes RE curtailment and works with grid operator through 2WC to provide support for grid. Independent Electricity System Operator (IESO) is used as an example and case study [67]. The rest of the chapter is organized as: (4.2) IESO Market, (4.3) Wind – BESS Model, (4.4) Proposed

PEMCC Model, (4.5) Simulation and Results, and (4.6) Conclusions. Wind resources forecasting is outside the scope of this work; interested readers are to referred to [94 – 96].

4.2 IESO MARKET

Modern utilities/grids typically project the following day electricity/load demand. Then they run their optimization programs to identify the cost-effective way to meet the demand. Different combinations of available generating units are scheduled to operate the following day with defined start, operation and turn off times. Energy supply mix may include nuclear, hydroelectric, wind or other sources based on their cost and/or utility mandated energy sources supply mix structure. The decision of more or less generation is made by ramping up or down and committing or de-committing units in real-time to keep supply and demand balanced. Any error or difference in forecast and commitment is settled/paid at real-time prices with or without penalties. Real-time prices can be lower, equal or greater than DAC prices and thus may cause revenue loss. Additional revenue is possible if penalties are part of the price schedule. Therefore, authors deem it necessary to equip the reader with a utility or grid operator day to day operations to appreciate the proposed PEMCC model. For further details, refer to [67].

IESO uses DAC process advanced scheduling and commitment of resources required to meet the next day's expected demand to address power system reliability concerns. Therefore, each day, IESO issues forecasts and posts of expected energy consumption (demand) for the next day (over 24h). Typically, the forecasts are very good, with less than two percent variance from the actual demand. Suppliers (electricity generators and importers) review the next day's forecasted demand posted by IESO to anticipate and decide on the amount of electricity supply and its price. Subsequently send their offers (supply and price) to the IESO. In a similar way, a small number of significant customers submit a bid (consumptions and price) to the IESO market. If the market's clearing price is greater than the customers' bid price, the customers stop consuming electricity.

The IESO then matches the offers to supply electricity against the forecasted demand (over 24h). Pre-dispatch collection of bids and offers continues until 2 hours before the energy is needed, with prices fluctuating throughout the window. IESO then sets the market price by stacking offers. This step is known as "offers stack." Offers stack adds first the forecasted RE generation offers, then the lowest priced offers, and continues to stack price offers until enough has been accepted to meet demand. IESO uses the last accepted offer price, the market clearing price, to pay all suppliers. The IESO then instructs (dispatches) suppliers based on their winning offers to provide electricity to the grid. Additionally, on call operating reserve suppliers are paid operating reserve payments, determined by the IESO market. These operating reserve suppliers remain on call to provide energy when the generator(s) break down unexpectedly, or when there is a generation dip or demand spike. Then IESO sets hourly Ontario energy price, the average of twelve 5-minute market clearing prices in an hour, based on the offers, bids and operating reserves, and charges the hourly Ontario energy price to large buyers, such as market participating large customers (energy consumers) and local distribution companies (energy sellers).

Dispatchable generators (dispatchable in real time, able to respond to 5-minute dispatch instructions and modify production) are required to submit their initial dispatch data between 06:00 and 10:00 East Standard Time on the previous day. Dispatchable generators dispatch data including supply and price offers for each hour of the day and are able to adjust the amount of electricity they produce in response to the new instructions issued every 5 minutes by the IESO. Additionally, dispatchable loads (dispatchable in real time, able to respond to 5-minute dispatch instructions and modify consumption) that want to participate as dispatchable in real-time are required to submit dispatch data by 10:00 East Standard Time on the previous day. Dispatchable loads, if participating, similar to dispatchable generation must be able to adjust power consumption in response to new instructions issued every 5 minutes by the IESO. Dispatchable loads must reduce consumption to meet their dispatch instructions, if the energy price is greater than their bid price. On a similar basis importers and exporters submit their offers by 10:00 East Standard Time on the previous day. Non-dispatchable but controllable generators such as wind (able to respond to 5-minute dispatch instructions to modify production in their operational limits and prevailing wind resources), also submit their 24h energy production forecasts, hour by hour, without attaching any price to it. Non-dispatchable generators and loads (not able to respond to 5-minute dispatch instructions) are not required to submit any production and consumption estimates or offer and bid prices. All non-dispatchable generators (controllable or not) receive or pay hourly Ontario energy price defined by IESO market clearing prices.

IESO maintains system reliability through consumers and generators performing different roles, and continuously balancing energy supply and demand. Run-of-the-river hydro facilities and nuclear power plants operating as baseload generators provide basic energy needs around the clock by producing a constant and steady output with little to no downtime. Usually, able to decrease or increase their output to a limited degree, these facilities are invoked only when electricity demand falls below the output of baseload generators. On the other hand, natural gas facilities and hydro generators with reservoirs are used to increase and decrease energy output as required. These generators are also relied upon to meet the peaks on the highest demand days of the year, and are brought in quickly when scheduled generator(s) breaks down unexpectedly. The outputs of other types of generators are adjusted throughout the day as consumer demand ramps up and down.

IESO uses variable RE generators, such as wind facilities, as baseload supply to meet core energy demand needs by adding them to the offers stack first. Energy output of these generators is variable; however, these generators are highly flexible within their limits (operational and resources availability) and, if required, can change their output very quickly. Therefore, IESO has a dispatch process for wind facilities connected to the grid which is used to decrease or increase their output depending on power system conditions. IESO uses dispatch when there is surplus base generation to follow changes in demand in order to keep supply and demand balanced, and to reduce congestion along transmission lines.

4.3 WIND – BESS MODEL

WECS generated power (P_W, wind power) at any instant is given by equation (1), where ρ, r, and V are air density, rotor radius, and wind speed, respectively.

$$P_W = 0.5\rho\pi r^2 V^3 \tag{4.1}$$

Multiplying equation (4.1) by time t gives WECS electrical energy (E_W), given by equation (4.2), which can be used with turbine power curve to estimate wind energy for a given V.

$$E_W = 0.5\rho\pi r^2 V^3 \mathrm{t} \tag{4.2}$$

BESS is connected across DC link of WECS and thus output of the model is limited to WECS rated power ($P_{w\text{-}rated}$) given by equation (4.3), where P_o is output, P_w is wind, and P_B is BESS power.

$$P_O = P_W + P_B \leq P_{W-rated} \tag{4.3}$$

IESO electricity market operates based on DAC with 24h ahead forecasts. Thus the theoretical maximum energy needed to be stored/supplied, if the forecast goes completely wrong (100% FE), is given by equation (4.4), where t = 24 hour.

$$E_{B-max} = P_{W-rated} t \tag{4.4}$$

However, since the maximum FE is limited to 25% of rated capacity over 24h horizon [93], 100% FE is not probable. Therefore, BESS size can be reduced as in equation (4.5), where $E_{B\text{-}DAC}$ is BESS energy required in 24h. Note that it is unlikely that FE will cause only surplus (or only shortage) over 24h, therefore, one might seek to further reduce BESS size even at the expense of limiting "on-request" grid support.

$$E_{B-DAC} = 0.25 E_{B-max} \tag{4.5}$$

Therefore, for 1.5MW WECS, the required storage would be 0.375MWh. With a depth of discharge of 80%, $E_{B\text{-}DAC} \approx 0.45$MWH.

4.4 PROPOSED PEMCC MODEL

At present, IESO sends one-way dispatch instructions to WECS, when there is surplus baseload generation, supply and demand balance issues (supply > demand), and transmission line congestion. However, the 2WC, a part of the proposed PEMCCS model, enables WECS to "offer" and IESO to "bid." In other words, PEMCCS can not only receive IESO dispatch instructions but also provides IESO with the required DAC and hourly estimated energy (HEE) forecasts in advance for the upcoming 24h cycle, and pro-actively communicate and coordinate operations every Δt (5 minutes) for next Δt, 288 times ($24x60/\Delta t = 288$) a day. The PEMCCS and IESO cooperative approach allows PEMCCS to optimally minimize RE curtailment, assure E_{DAC} delivery, adjust/control power injection magnitude, compensate for forecast errors, and inject rather smoother power into grid. On the fly power smoothing is not the focus of the work, rather a by-product of the process. Five-minute Δt operational unit is selected for PEMCCS to match IESO 5-minute operational resolution.

A: Formulation

Equations (4.6) and (4.7) are used to estimate 24 E_{HEE} and E_{DAC} to be provided to the IESO for the next 24h cycle. Equation (4.6) uses 288 power injection levels (P_{CF}) to establish 24 E_{HEE} while equation (4.7) estimates E_{WDAC} where n=12, q=24, Δt=5 minutes, and j=24.

$$E_{HEE}(U,p) = \sum_{p=0}^{q-1} \sum_{m=0}^{n-1} P_{CF} \Delta t \tag{4.6}$$

$$E_{DAC} = \sum_{i=0}^{j-1} E_{HEE} \tag{4.7}$$

Similarly, Equation (4.8) limits $P_{BF}(k)$, BESS power at time $k=\Delta t$, to the max charge/discharge limits of BESS, given by $P_{B\text{-}max}$ and $P_{B\text{-}min}$. Equation (4.9) keeps $E_{BF}(k)$ in BESS limits of charge and level of depth of discharge. Equation (4.10) gives $E_{BF}(k)$, change in BESS energy during Δt, using the past interval BESS energy $E_{BF}(k-1)$ and the present energy change $P_{BF}(k)\Delta t$. Efficiency is $\eta=1/\eta_c$ for charging and $\eta=\eta_d$ for discharging. Equation (4.11) ensures final BESS energy (E_{Bf}) equals the initial BESS energy (E_{Bi}); BESS power remains unchanged at the end of the 24h cycle.

$$P_{B-min} < P_{BF}(k) < P_{B-max} \tag{4.8}$$

$$E_{B-min} < E_{BF}(k) < E_{B-max} \tag{4.9}$$

$$E_{BF}(k) = E_{BF}(k-1) + \eta P_{BF}(k)\Delta \mathrm{t} \tag{4.10}$$

$$E_{Bf} = E_{Bi} \tag{4.11}$$

Equation (4.12) keeps $P_{OF}(k)$ limited to WECS rated power. Equation (4.13) limits change in $P_{WF}(k)$ to the $P_{o\text{-}max}$ in (4.12), with P_{OF} direction of change tracked by D(k+1) and U(k+1) from one moment (k-1) to the next (k). D(k+1) and U(k+1) represent POF change down (D) and up (U).

$$0 = P_{W-min} < P_{OF}(k) = P_{WF}(k) + P_{BF}(k) < P_{W-max} = P_{W-rated} \tag{4.12}$$

$$-P_{O-max}D(k+1) < P_{OF}(k) - P_{OF}(k-1) < P_{O-max}U(k+1) \tag{4.13}$$

Equations (4.14) and (4.15) restrict changes in U(k) and D(k) to either logical 0 (down) or 1 (up). U(k) and D(k) assume value of 1 when the output increases and decreases, respectively. Sum of U(k) and D(k) results in either between 0 or 1 (logical summation), since the output can either go up or down at a time.

$$0 < U(k) < 1 \tag{4.14}$$

$$0 < D(k) < 1 \tag{4.15}$$

$$0 < U(k) + D(k) < 1 \tag{4.16}$$

The objective function to minimize predictive P_{CF}, given by equation (4.17), is minimized subject to (4.8) – (4.16). M equals 288. Note that solution set (U) is obtained every Δt with M–k members. Solution set shrinks by k (Δt or i) each successive k, with i increasing by 1 successively.

Minimize: $$J(U, M-k) = \sum_{k=i}^{M-1}(Uk + Dk) \tag{4.17}$$

Next, the objective function in equation (4.18) is minimized subject to (4.8) – (4.10) and (4.12) to make EMC decisions, where M=288, Δt=5 minute intervals over 24h horizon, and C_E is the cost of penalty. P_{CE} (k), the difference between predictively-committed power (P_{CF}(k)) and the sum of forecasted WECS power (P_{WF}(k)) and power from/to BESS (P_{BF}(k)) is given by equation (4.19). Note that solution set is obtained at each Δt (or k), but over successively shrinking (M–k) horizon.

Minimize: $$J(U, M-k) = \sum_{k=i}^{M-1} C_E(k) P_{CE}(k) \Delta \mathrm{t} \tag{4.18}$$

$$P_{CE}(k) = P_{CF}(k) - P_{WF}(k) - P_{BF}(k) \tag{4.19}$$

Equation (4.20) is used to estimate possible curtailment (Curl) in the remaining 288–k Δt's, while equation (4.21) gives the difference (S) between the updated P_{WF} and the originally forecasted P_W. Equation (4.22) estimates the difference between wind energy available and wind energy delivered (E_{WD}) into grid up to the k^{th} Δt. Equation (4.23) redefines DAC energy (E_{DAC}) given by equation (4.7) to compensate for any surplus (or shortage) of energy across BESS at the end of the 24h cycle, possible due to forecast errors and IESO dispatch instructions.

$$Curl = \sum_{k}^{M-k} P_{WF}(k)\Delta \mathrm{t} - \sum_{k}^{M-k} P_W(k)\Delta \mathrm{t} \tag{4.20}$$

$$S = P_{WF}(k) - P_W(k) \tag{4.21}$$

$$E_{WD} = \sum_{j=1}^{j=k} P_{WF}(k)\Delta \mathrm{t} - \sum_{j=1}^{j=k} P_{CF}(k)\Delta \mathrm{t} \tag{4.22}$$

$$E_{DAC} = E_{WDAC} + (E_{Bf} - E_{Bi}) \tag{4.23}$$

Finally, equations (4.24) and (4.25) give IESO dispatch instructions (DI) in terms of dispatch down (DD) and up (DU), respectively.

$$DI- = P_{CF}(k) - DD \tag{4.24}$$

$$DI+ = P_{CF}(k) + DU \tag{4.25}$$

B. Algorithm

Figure 4.1 shows the proposed PEMCCS algorithm. First, based on the given WECS specifications, 288 P_W are established using forecasted wind speeds (288 samples) over 24h horizon. Then, 288 P_W are used with BESS to define 288 power injection magnitudes, P_{CF}, (Equations (4.9) to (4.17)) with minimum number of level changes for power injection into IESO grid. Next, 288 P_{CF} are used to establish 24 E_{HEE} using equation (4.6) and E_{DAC} using equation (4.7) and these are communicated with IESO for the upcoming 24h cycle.

At one Δt before the beginning of 24h cycle, PEMCCS steps into the predictive EMC portion of algorithm over 288–k Δt's horizon. The updated 288–k forecast with k=0 wind data is assessed to estimate the updated 288–k wind power forecasts (P_{WF}). Then, 288-k P_{WF} with BESS status are used to define 288–k P_{CF} power injection levels with minimum level changes. Next, PEMCCS takes P_{CF}, 288–k P_{WF}, and BESS status and make 288–k (since k=0) operational decisions during this Δt (present Δt, t=k). Then, the first set of the 288-k decisions is selected to be applied at next Δt (future Δt, t=k+1). System status ("offer") with the proposed power injection and BESS status for the next Δt is communicated with IESO, IESO instructions ("bid") are received, and the system is operated accordingly in the next Δt. IESO may "bid" an "offer," instruct dispatch up (DU) in the WECS operating limits at next k, or instruct dispatch down (DD) to even zero injection. The process is repeated with 288–k (287, since k=1) and operational decisions are made again, using the updated 288–k P_{WF}, 288–k P_{CF}, and 288–k BESS status, to be applied at the next Δt (k=2). This process is repeated and PEMCCS is executed 288 times, with shrinking (288–k) horizon, every Δt to be applied at the next Δt. The PEMCCS scheme automatically modifies the operational behaviour, by modifying P_{CF} level to account for wind energy excess (FE+) or shortage (FE-) and to follow IESO dispatch up (DU) or down (DD) instructions while minimizing curtailment and without compromising E_{DAC} delivery. Note that, the remaining 288–k P_{CF} are always redefined when FE is observed or dispatch instruction is received. Since IESO always has the system's status, it is the responsibility of IESO to keep DD & DU in the deliverable limits for the next Δt.

PEMCCS make predictive EMC decisions every Δt, communicate with IESO, and operate in harmony with IESO following IESO dispatch instructions to optimize resources and support grid operations. This way, PEMCCS moves into the future Δt step at a time with the 288–k Δt's forecasts updated every Δt. PEMCCS decisions revision every Δt over updated and shrinking (288–k) Δt's horizon that 1) serves as a self-correction mechanism, 2) minimize impact of forecast error, 3) allows 2WC every Δt, 4) minimizes RE curtailment, 5) ensures E_{DAC} delivery, and 6) supports grid at matching resolution, and 7) injects rather smoother power into grid. PEMCCS and IESO matching resolution allows better management RE resources through coordinated decisions with the predictively available system potential for the next Δt, renewed every Δt.

Thus two-way communications ensure cooperation between PEMCCS and IESO by operating WECS plus BESS system in IESO-Following mode to support IESO operations based on the operational scenarios such as supply and demand issues and surplus base generation across grid. Note that PEMCCS "offer" and IESO "bid" have no prices attached (since IESO pays WECS by Hourly Ontario Energy Price). However, increased revenue is possible with the PEMCCS model though energy delivery advancement (delay), if time of use prices are part of tariff structure or futuristic energy consumption trend data is provided by IESO.

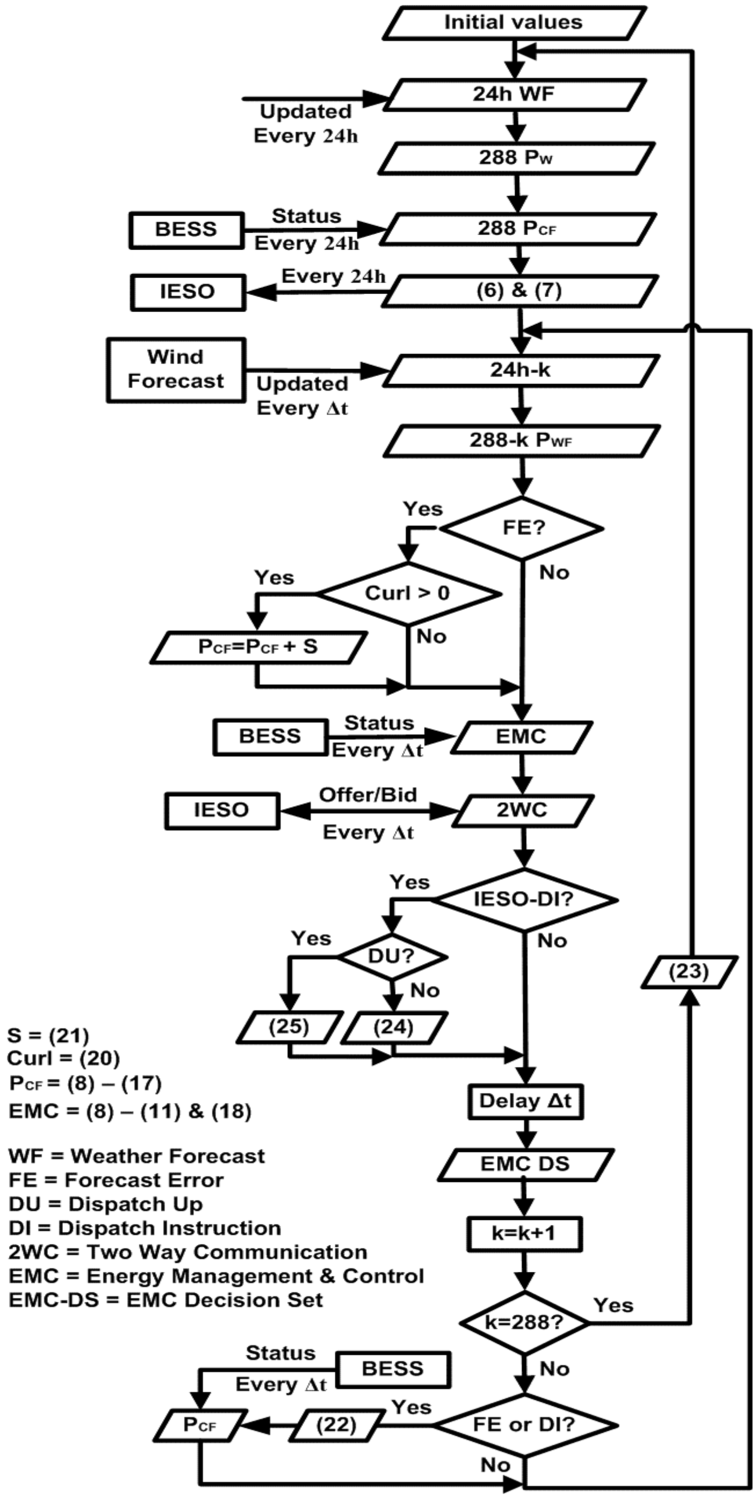


Fig. 4.1: Proposed PEMCC Algorithm

4.5 RESULTS AND DISCUSSION

As pointed out earlier, in this work 1.5MW wind system is used to estimate P_W and P_{WF} to illustrate the effectiveness of the proposed PEMCC model in different operating scenarios. Wind system is connected to IESO grid and the possible scenarios are tabulated in Table 4.1. Note that Case #13 – #16 are not applicable (N/A) since IESO cannot instruct DU and DD at the same time. To limit the number of graphs, only a selected number of scenarios are reported.

Table 4.1: Operating Scenarios

Case #	DU	DD	FE+	FE-	Comments
1	0	0	0	0	No IESO DU, DD, & forecast error
2	0	0	0	1	No IESO DU, DD but Dec. P_{WF}
3	0	0	1	0	No IESO DU, DD but Inc. P_{WF}
4	0	0	1	1	No IESO DU, DD but Inc. P_{WFi} & Dec. P_{WFj}
5	0	1	0	0	No forecast error but IESO DD
6	0	1	0	1	Dec. P_{WF} & IESO DD
7	0	1	1	0	Inc. P_{WF} & IESO DD
8	0	1	1	1	Inc. P_{WFi}, but Dec. P_{WFj} & IESO DD
9	1	0	0	0	No forecast error but IESO DU
10	1	0	0	1	Dec. P_{WF} & IESO DU
11	1	0	1	0	Inc. P_{WF} & IESO DU
12	1	0	1	1	Inc. P_{WFi}, Dec. P_{WFj} & IESO DD

Note: Inc.=Increased, Dec.=Decreased, DU=Dispatch Up, & DD=Dispatch Down

Fig. 4.2. plots wind profile (subplot-1) and the corresponding wind system generated P_w (subplot-2) over 24h horizon with 288-k Δt. Wind speed ranges between 6 m/Δt (cut-in wind speed) to 14 m/Δt (rated) with corresponding P_W = 0.12MW to P_W = 1.47MW (0.03 MW losses). Note that P_W also represents the fluctuating power injected across the grid each Δt without PEMCC (or any other type of fluctuation removal algorithm).

Fig. 4.3 plots 24 HEEs (subplot-1) and total energy (subplot-2) to be delivered over 288 Δt's. DAC and 24 HEEs are supplied to the IESO (grid operator) for the next 24h cycle and are tracked by PEMCC over 24h shrinking horizon to meet DAC, hour by hour (and Δt by Δt) while achieving other goals identified earlier. DAC supplied to IESO is 125.47MWh, and 24 HEEs are [3.4550, 4.3558, 5.4875, 4.16, 9.8467, 3.7, 4.3083, 8.8217, 6.3083, 4.3167, 4.897, 4.7438, 4.2189, 4.2189, 4.2863, 5.344, 3.606, 4.3444, 5.2456, 9.02, 7.14, 4.36, 4.54, 4.745] x 1e6. Note that each HEE consists of 12 small energy delivery estimates (12 Δt/h).

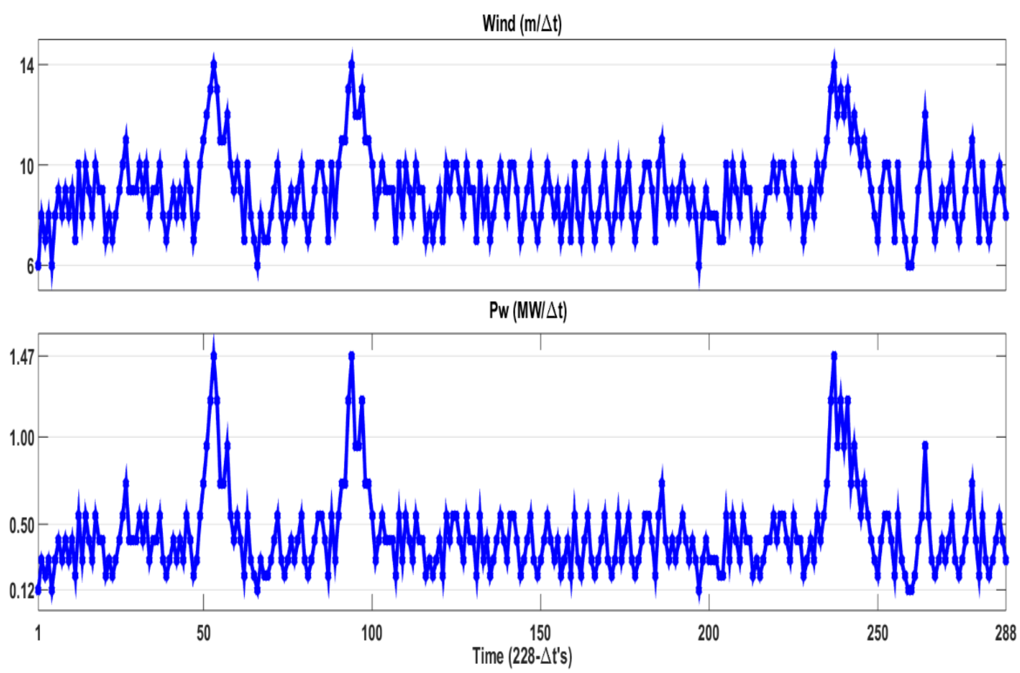


Fig. 4.2: Wind and P_w over 288 Δt

Figures 4.4 to 4.6 discuss case #1 (the ideal case) in Table 4.1, when no forecast error is observed and no DI is received over 24h horizon (288 Δt's). In other words, the actual wind power and the forecasted wind potential provided to IESO perfectly match. PEMCC defines P_{CF} (**black)** using

Eq. (10) - (19) with minimum number of level changes (Fig. 4.4) to inject smoother power with 34 reference levels instead of 288 P_{WF} (**blue**) varying levels.

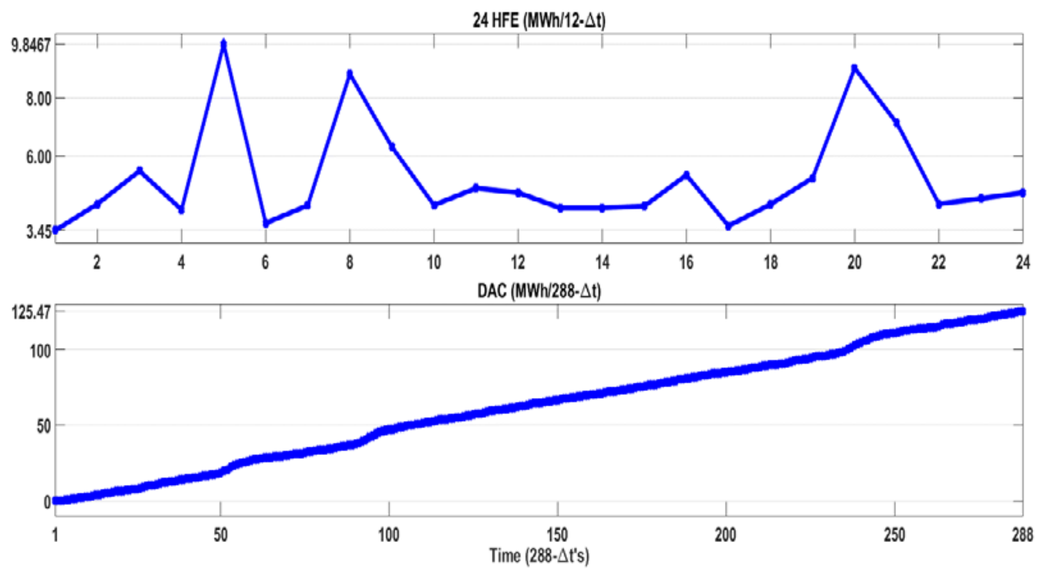


Fig. 4.3: 24 HEEs (E_{HEE}) and 1 DAC (E_{WDAC}) over 288 Δt

Fig. 4.5 sheds light on EMC and 2WC portion of the PEMCC model for case #1. Close analysis of Figure 4.5 reveals that the defined P_{CF} (**black**) is perfectly delivered by PEMCC, managing and appropriately controlling BESS P_B (**Cyan**). In other words, power is delivered into grid per defined P_{CF} with 34 power injection levels by EMC (Eq. (10) – (13) & (20)) plus 2WC with IESO, shown as P_{WB} (**magenta**, combined P_W & P_B) in Fig. 4.4. The error defined by equation (21), shown as P_{CE} (**red**), remains zero throughout the 24h indicating perfect delivery of power. Finally, Fig. 4.6 shows that the total actual energy delivered (**green**) equals 125.47MWh (DAC committed, **blue**). Thus BESS energy shows no change and the final BESS energy (E_{Bf}) equals the initial BESS energy (E_{Bi}). Note that 288 P_{CF} defined by PEMCC can range from 1 (best) to 288 (worst) reference levels, and for the same wind data the larger BESS sizes will result in lower reference levels.

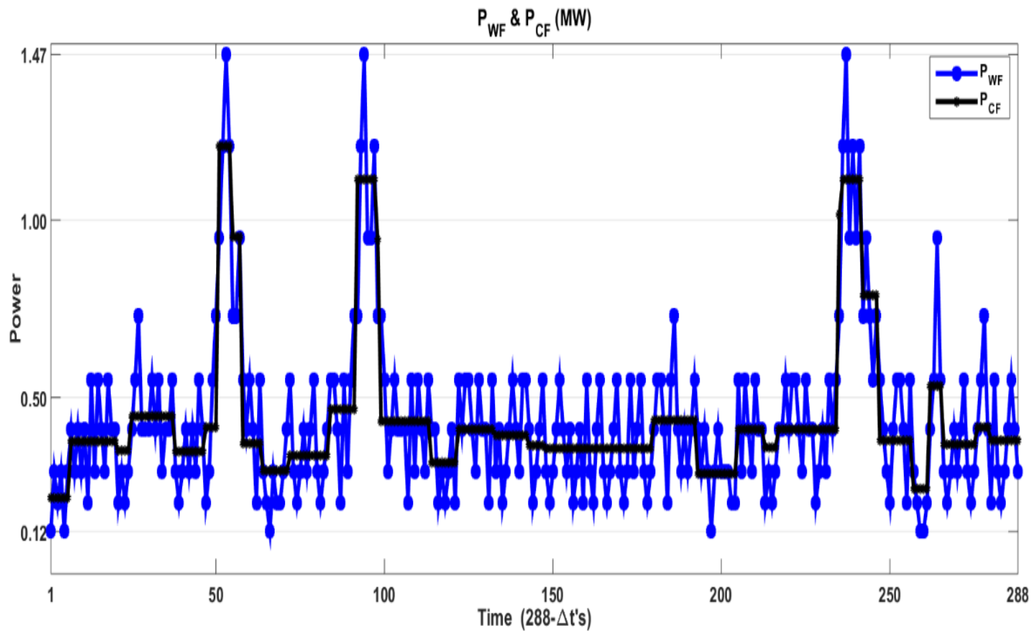


Fig. 4.4 Case #1 – P_{WF} & P_{CF} over 288 Δt

Case #2 in Table 4.1 is simulated by introducing forecast errors at 24th and 71st Δt. In other words, wind changes at 24th Δt from 8 m/Δt to 7 m/Δt causing P_{WF} to change from 0.29MW to 0.2MW, observed at 23rd Δt, and from 9 m/Δt to 8 m/Δt for 71st Δt causing a change of 0.12MW (0.41MW to 0.29MW), observed at 70th Δt. Notice that both forecast error cause P_{WF} to decrease and total change in energy is 0.21MWh (observed n Δt's apart). Since there is no change until k=23 in the next Δt, Fig. 4.4 to 4.6 are valid for k=1 to k=23. However, due to change for k=24 observed at k=23 (with no change at 71st Δt observed yet), figures 4.4 to 4.6 become invalid and a new operational strategy needs to be defined. Fig. 4.7 shows revised P_{CF} for the remaining 265 Δt's (k=24 to k=288). However, another forecast error is observed at k=70 for k=71 and the P_{CF} defined at k=24 for the remaining 265 Δt's becomes invalid. Therefore, as shown in Fig. 4.8, PEMCC defines another operational strategy for the remaining 218 Δt's (k=71 to k=288).

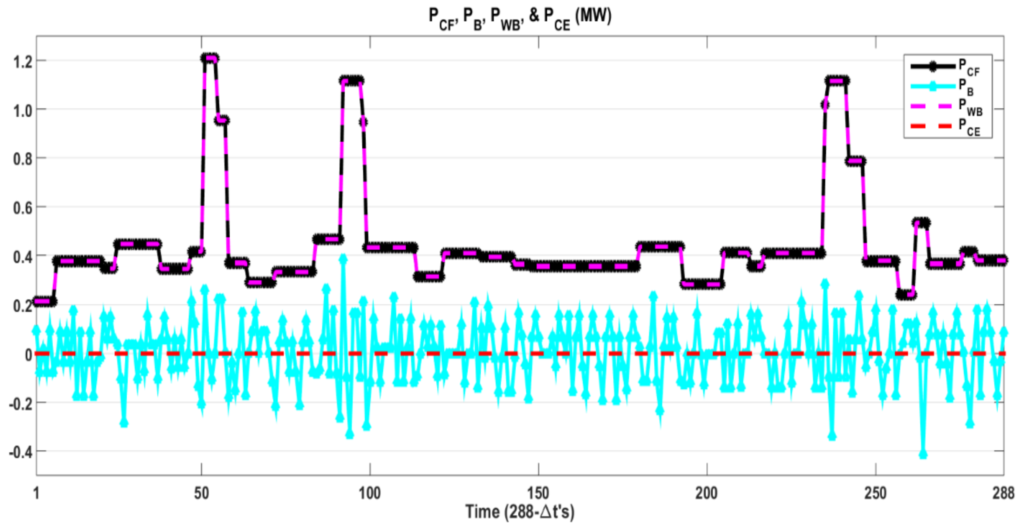


Fig. 4.5: Case #1 – P_{CF}, P_B, P_{WB} & P_{CE} over 288 Δt

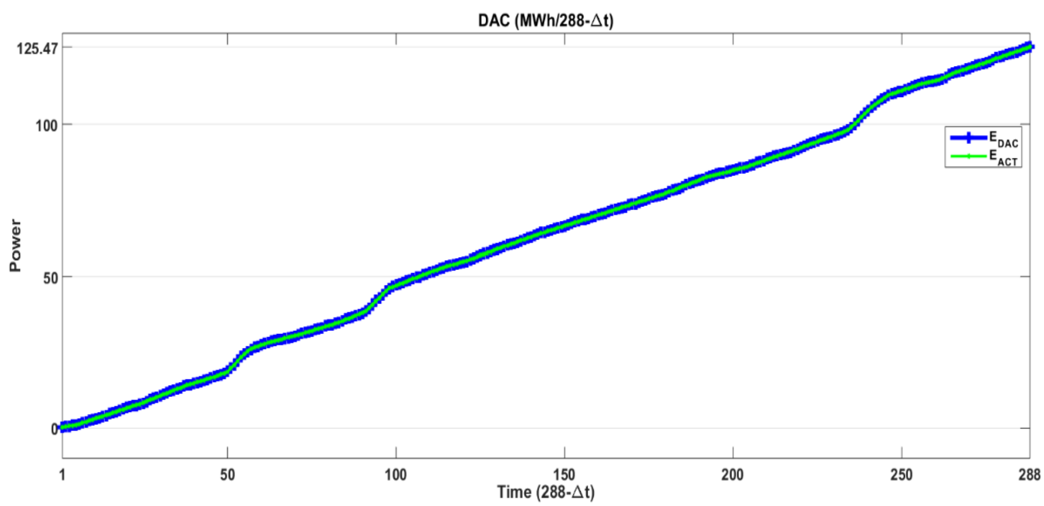


Fig. 4.6: Case #1 – DAC (E_{WDAC}) & Actual Energy (E_{ACT}) delivery over 288 Δt

Fig. 4.9 shows the cumulative P_{CF} defined (k=1 to 23, 24 to 70, and 71 to 288) and followed by PEMCC. Similar to what was observed in Fig. 4.7 to 4.9, three energy delivery scenarios were created (k=1 to 23, 24 to 70, and 71 to 288) by PEMCC; however, only the cumulative version is shown in Fig. 4.10.

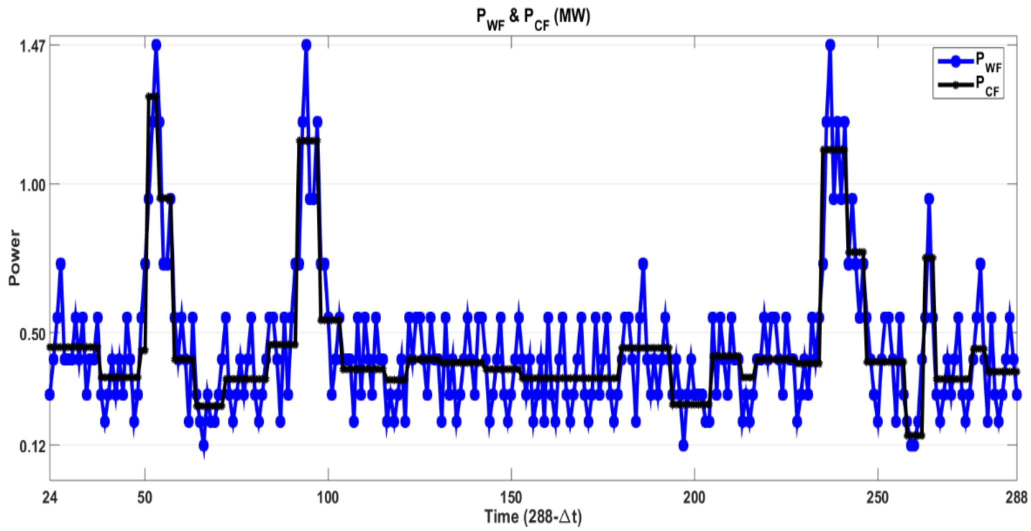


Fig. 4.7: Case #2 – P_{WF} & P_{CF} over 265 Δt

Detailed analysis of Fig. 4.7 to 4.10 reveals that: 1) P_{CF} was defined three times (due to 2 additional forecast errors), 2) cumulative P_{CF} has 33 power injection levels instead of 34 in spite of 2 forecast errors (compare Fig. 4.9 and Fig. 4.5), 3) the total energy delivered is still 125.47MWh (shortage supplied by BESS), 4) 2WC concluded no IESO dispatch instructions and thus the 1st decision out of 288-k EMC decisions was applied to operate the system for the next Δt, 5) system looped back for another k (or Δt) with (at 24th and 71st) or without defining a new operational strategy. Note that FE- (decrease in P_W) causes BESS energy to shrink since it is supplied by BESS. To compensate for change and to avoid shrinkage (or expansion) over the 24h cycle and to ensure effective utilization of BESS, equation (22) was included in the algorithm.

Similar to FE-, PEMCC also redefines the operational strategy for FE+ (case #3 in Table 4.1). The difference is the fact that, if PEMCC estimates excess of wind energy over the remaining 288-k Δt's (actual energy is greater than DAC provided to IESO) and curtailment is evident, then

PEMCC redefines P_{CF}, increasing injection into grid in coordination with IESO through 2WC to avoid curtailment/waste of RE.

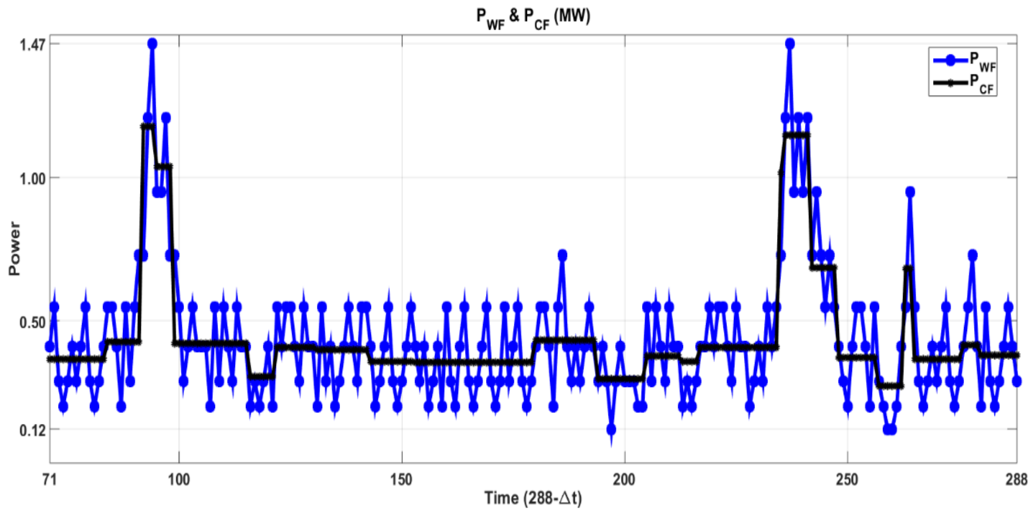


Fig. 4.8: Case #2 – P_{WF} & P_{CF} over 218 Δt

As for case #4 in Table 4.1: 1) PEMCC takes no action if FE+ (or FE-) observed at k for k+m Δt is being compensated by FE- (or FE+) observed at k for k+n Δt (equal FE+ and FE- observed at k simultaneously for k+m and k+n Δt, respectively) over the remaining horizon, 2) PEMC redefines P_{CF} to increase (or decrease) power injection level by FE+ (or FE-) observed at k for k+m Δt is greater (or smaller) than FE- (or FE+) observed at k for k+n Δt over the horizon. The same concept applies to any combination of more than 2 forecast errors. If 2 or more FE+ or FE- are not observed simultaneously, then case #2 and case #3 of Table 4.1 apply.

Fig. 4.11 shows case #5 of Table 4.1. No forecast error was observed throughout the day; however, IESO dispatch instructions was received through 2WC at the 91st Δt. PEMCC, following the procedures outlined before, has planned injection into the grid at the next Δt (92nd), but IESO instructed PEMCC to limit power injection to 0.5MW (DD=0.5MW). Note that the 92nd k has a wind speed of 11 m/Δt with a P_{WF} of 0.73MW and PEMCC planned power injection level of 1.115MW (Fig. 4.4). PEMCC revises the injection plan for the next k using with DD=0.5MW and equation (26) to modify P_{CF} and restrict injection to the IESO defined limit. Next, PEMCC redefines P_{CF} injection to absorb this change (compare Fig. 4.5 and Fig. 4.11). Note that this is a DD not DU, and IESO can exploit the whole range from rated down to zero. As pointed out earlier, PEMCC will simply follow IESO instructions; however, IESO dispatch instructions may cause partial or full curtailment if BESS does not have enough room for storage at that specific k (curtailment evidently would have occurred, for example, if the same 0.5MW DD was received at 93^{rd} k for 94^{th} Δt). The total number of reference levels goes up by one to 35 (compare Fig. 4.5 and Fig. 4.11). The same procedure is followed by PEMCC for more than 1 DD from IESO. In this case, DAC is met and $E_{Bf} = E_{Bi}$ (Fig. 4.12).

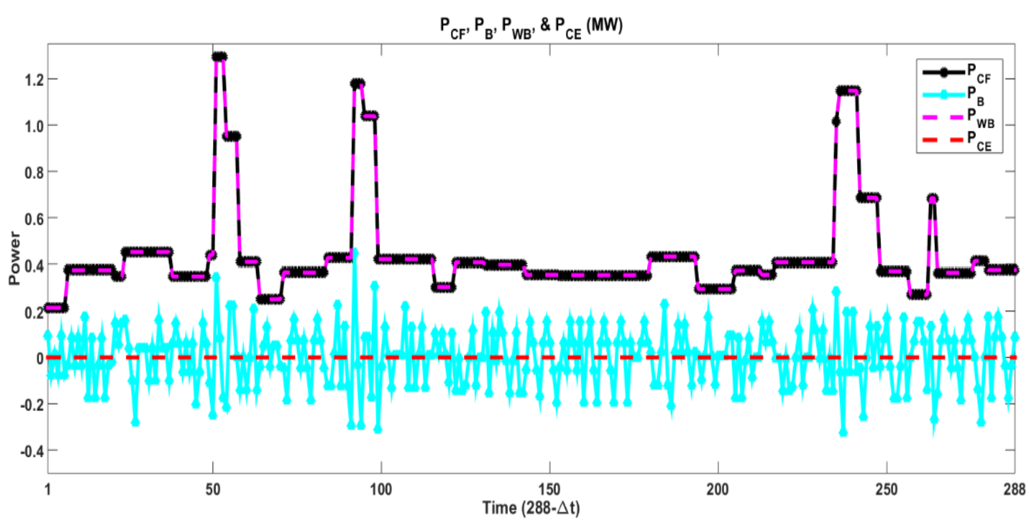


Fig. 4.9: Case #2 – P_{CF}, P_B, P_{WB} & P_{CE} over 288 Δt

Similar operational philosophy will be followed for case #9 in Table 4.1, with a DU. However, instead of equation (26), equation (27) will be used to define injection level for next k, followed with a redefinition of the P_{CF} to absorb change. Since IESO is provided with the proposed injection level for the next Δt and BESS status, IESO shall limit, DU in the deliverable limits.

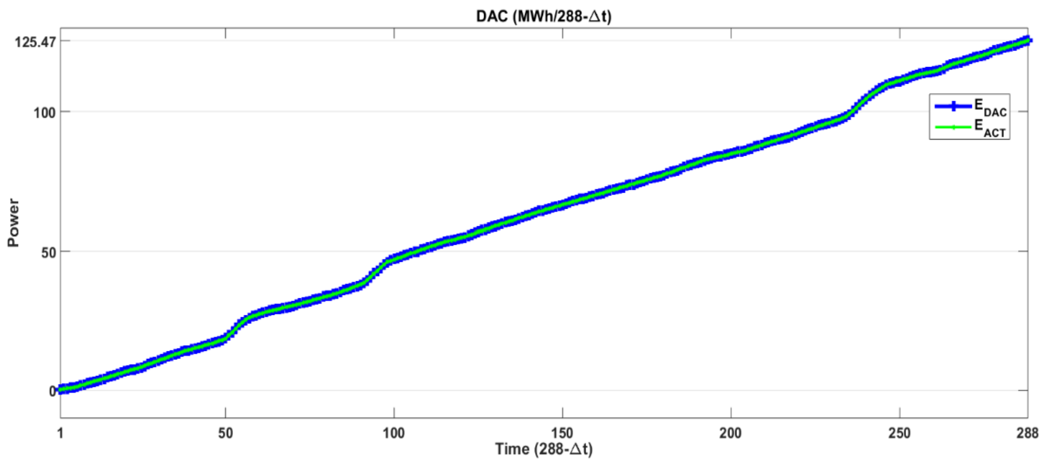


Fig. 4.10: Case #2 – DAC (E_{WDAC}) & Actual Energy (E_{ACT}) delivery over 288 Δt

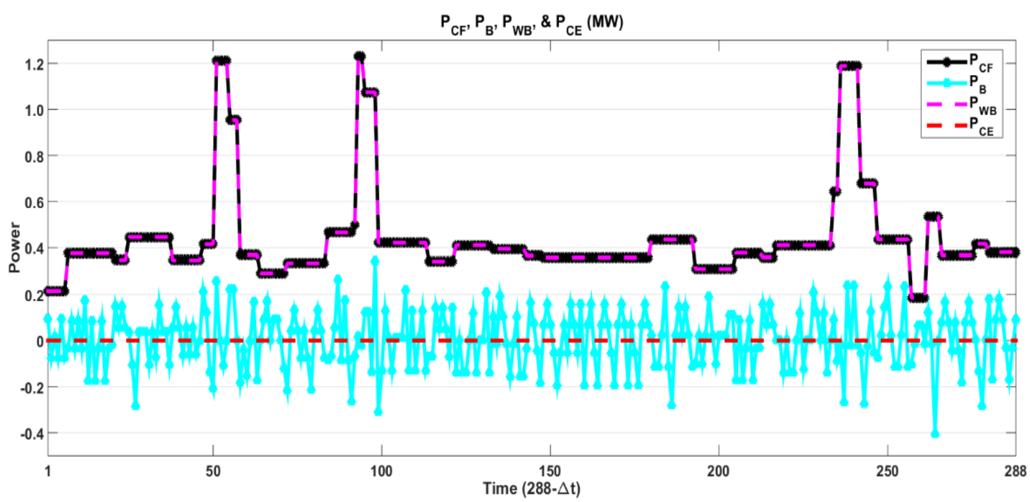


Fig. 4.11: Case #5 – P_{CF}, P_B, P_{WB} & P_{CE} over 288 Δt

Assume FE- observed at 70th k for 71st Δt (as discussed before) with DU=0.335MW at 93rd k for 94th Δt through 2WC (case #10 in Table 4.1 with both decreased P_W and DU). As discussed before, PEMCC had planned injections for both 71st and 94th Δt's; however, it is required to compensate for FE- as well as supply IESO DU. Since FE- and DU=0.335MW are m Δt apart, PEMCC defines the operational philosophy as 1) case #1 up to 70th k, 2) case #2 from 71st to 93rd k, and 3) case #9 onward. Fig. 4.13 shows the cumulative results. Changes in the PEMCC operational philosophy can be observed at 71st and 94th k in P_{CF}, P_{WB}, and P_B (compare with Fig. 4.5). The number of injection levels goes up by 1 to 35 from 34 in Fig. 4.5. P_{CE} (red line) equals to zero throughout showing that PEMCC has perfectly defined P_{CF} and have controlled BESS to deliver DAC.

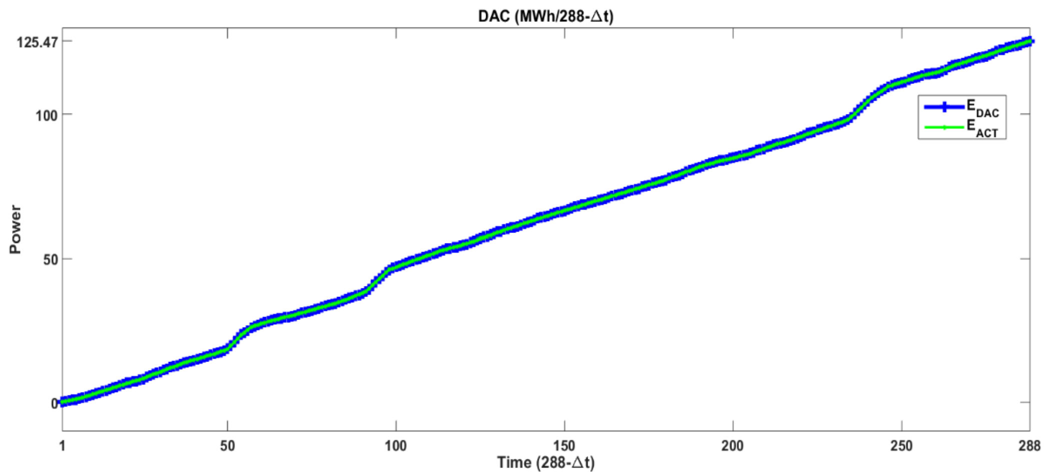


Fig. 4.12: Case #5 – DAC (E_{WDAC}) & Actual Energy (E_{ACT}) delivery over 288 Δt

Fig. 4.14 represents case #10 in Table 4.1 with both decreased P_W and DU. However, forecast error is observed and DU=0.335MW is received at 70th k for 71st Δt (or at 93rd k for 94th Δt) through 2WC simultaneously. PEMCC has to revise the planned injections for 71st Δt to simultaneously compensate for FE- and supply IESO DU. Therefore, PEMCC defines operational philosophy as case #1 until 70th k, and case #10 onward, i.e., from 71st to 288th k as shown in Fig. 4.13. When both FE- (or FE+) and DU (or DD) for the next Δt are observed and received at the same time, PEMCC first redefines the new operational strategy by redefining P_{CF} to absorb forecast error, and then assesses IESO dispatch instructions to modify the newly defined P_{CF} to follow IESO instructions, and then once again redefines the operational scheme for P_{CF} for the remaining Δt's (72^{nd} to 288^{th}). Note that PEMCC prioritizes IESO dispatch instructions DU (or DD) over compensation of FE- (or FE+), in case both of them cannot be resolved simultaneously. Changes in the PEMCC operational philosophy can be observed at 71^{st} k in P_{CF}, P_{WB}, and P_B (compare Fig. 4.14 and Fig. 4.5). The number of injection levels have again gone up by 1 to 35 (compare Fig. 4.14 and Fig. 4.5). P_{CE} (red dashed line) remains zero throughout 24h showing that DAC is delivered. The rest of the cases in Table 4.1 can be easily explained by the same logic used for explaining these sample cases.

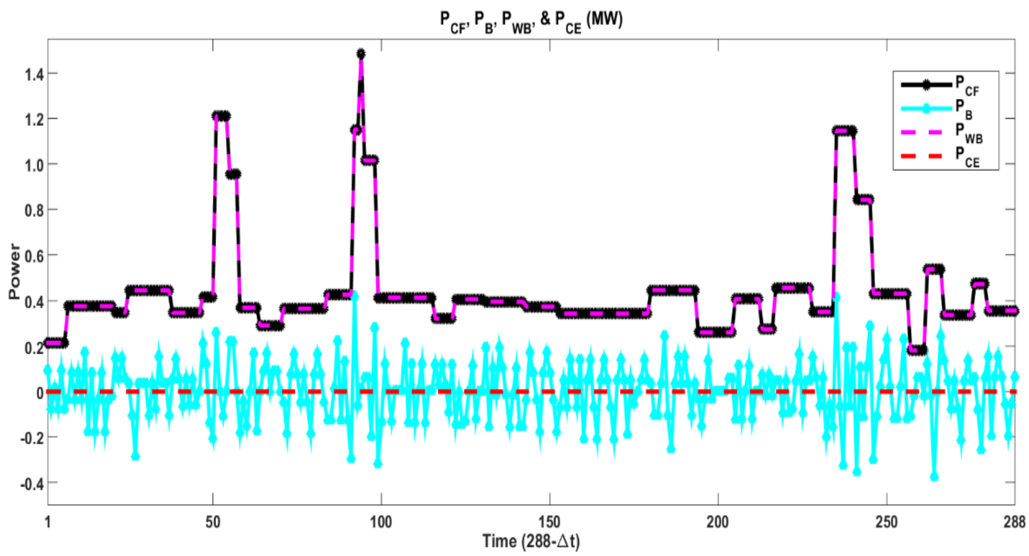


Fig. 4.13: Case #10 – P_{CF}, P_B, P_{WB} & P_{CE} over 288 Δt

Table 4.3 compares cases presented above. Comparing case# 2, 5 and 10 from the table with the ideal case (case # 1) reveals that the proposed algorithm ensures delivery of E_{DAC} and injects rather smoother power into grid in spite of FE and grid operator requests. Table 4.2 also shows case# 3 with FE+, where surplus was delivered into grid to minimize curtailment without affecting numbers of injection levels (34) inspite of levels redefinition due to surplus.

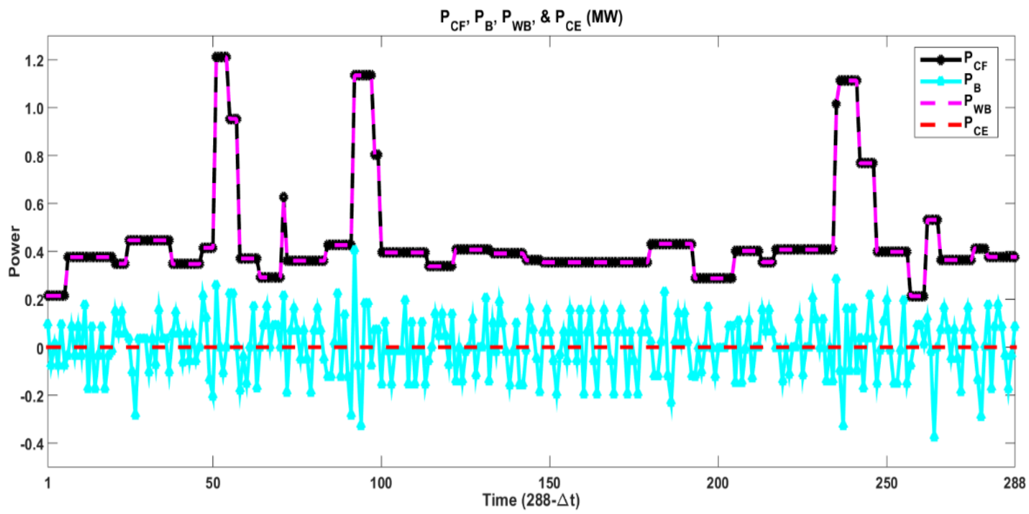


Fig. 4.14: Case #10 – P_{CF}, P_B, P_{WB} & P_{CE} over 288 Δt

Table 4.2: Selected Cases Comparison

Case #	FE	DI	# of Levels	Delivery
1	No	No	34	E_{DAC}
2	2	No	33	E_{DAC}
5	No	1	35	E_{DAC}
10	1	1	35	E_{DAC}
3	1	No	34	E_{DAC} + Surplus

4.6 CONCLUSIONS

In this chapter, PEMCC is proposed for Wind – BESS. PEMCC model uses wind forecast data over 24h horizon to define power injection into grid with minimum reference levels and then tracks it to deliver DAC. The proposed model accounts for forecast errors and facilitates 2WC with the IESO (grid operator) to coordinate power injection. IESO requests to increase or decrease power injection to accommodate the operational scenarios across the grid. The proposed model also minimizes the curtailment through 2WC with IESO. Though not implemented (future work), the proposed system has the capability to: 1) advance (or delay) energy delivery based on the present and future IESO operational conditions, if operational trend data is provided by IESO, and 2) exploit wind resources even further if TOU tariff is used by grid operator for wind systems payment. Results show the effectiveness of the proposed PEMCC model. The proposed model can be easily extended to wind farms or other RE (for example PV) sources.

Table 4.3 presents advantages of PEMCC through comparative analysis of the proposed PEMCC based Wind – BESS with CEMC based Wind and CEMC based Wind – BESS schemes.

Table 4.3: Comparative Analysis

	Wind CEMC	Wind – BESS CEMC	Wind – BESS PEMC
Curtailment	Yes	Yes	Minimum
Surplus at k	Increase Supply	Store	Store
Shortage at k	Decrease Supply	Supply	Supply
Surplus at k + n	No Action	No Action	Supply
Shortage at k + n	No Action	No Action	Store
Smoother Power	No	Static	Dynamic
IESO - DI	Down	Down	Up & Down
DAC Delivery	Weak Grid	Yes	Yes
Forecast errors compensation	No	No	Yes
Communication	1Wc	1WC	2WC
Grid Support	No	No	Yes
Optimization	No	k	k & k + n
Revenue	Sub-optimal	Sub-optimal	Optimal
Environment Friendly	No	Yes	Yes

CHAPTER 5

Conclusions and Future Work

5.1 RESEARCH CONTRIBUTIONS

This work proposed PEMC of RE systems. Specifically, PEMC of PV – BESS for TOU cost reduction, PEMC of PV – BESS for load shedding and weak grid support, and PEMCC of Wind – BESS for DAC delivery and smoother power injection into grid were presented. Focus was on PEMC to minimize the negative impacts of RE intermittency using 24h forecasted data. PEMC was successful in predictively making EMC decisions based on the present and future forecasted load (or commitments) and RE potential over 24h horizon to optimize resource use. PEMC was able to minimize curtailment, minimize supply and demand balance issues, BESS potential optimal exploitation, forecast errors compensation and rather smoother power injection into grid. Overall, PEMC increased RE proportions locally and/or into grid and resulted in increased savings or revenue for the system's owner.

The main contributions of each chapter of the thesis are listed below.

CHAPTER 2

PPEMC of grid-tied PV – BESS is proposed that reduces grid power consumption during TOU expensive on-peak periods and thus results in cost savings for the system owner. The proposed scheme foresees resources' potential and load demand over 24h horizon, with focus on on-peak periods, and predictively assess resources, evaluate potential outcomes, optimize use and make decisions to minimize curtailment and supply and demand issues in on-peak periods. The proposed scheme is proactive and makes predictive decisions as compared to passive CEMC techniques that make real-time decisions. PEMC ensures local energy supply during TOU expensive on-peak periods, fully exploits BESS potential and avoids unnecessary charging of BESS from grid. PEMC allows BESS charging during cheap off-peak periods (if required) and can advance (or delay) BESS energy to minimize PV curtailment and ensure local energy supply in on-peak periods. Repetition of decisions every Δt serves as a self- correction mechanism for the proposed scheme. PEMC provides:

- predictive resources allocation to meet present/future demand
- reduced PV curtailment
- optimal energy use
- BESS better exploitation through BESS energy advancement or delay
- TOU grid energy consumption reduction leading to increased savings

CHAPTER 3

PEMC of PV – BESS microgrid (operates in grid-tied as well as standalone modes) is proposed that reduces PV curtailment and ensures supply and demand balance in load shedding periods. The proposed scheme proactively foresees resources' potential and load demand over 24h horizon, with focus on load shedding periods, and predictively assess resources, evaluate potential outcomes, optimize use and make decisions to minimize supply and demand issues in load shedding periods. The proposed scheme is proactive and makes predictive decisions as compared to passive CEMC techniques that make real-time decisions. PEMC ensures local energy supply during load shedding crucial periods without compromising service reliability while minimizing PV curtailment. PEMC fully exploits BESS potential, allows BESS charging during nights (if required) while avoiding unnecessary charging from the grid. PEMC can advance (or delay) BESS energy to minimize PV curtailment and support weak grid with injection of PV power without compromising local energy supply in load shedding periods. Repetition of decisions every Δt serves as a self-correction mechanism for the proposed scheme. PEMC provides:

- reduces PV curtailment
- allocates resources to meet present/future demand focusing on load shedding periods
- minimizes loss of load in load shedding period
- enhances weak grid reliability through reduced PV curtailment
- allows full exploitation of BESS through predictive use/allocation of BESS energy
- increases PV (reduces grid energy) which translates into greater savings for customer

CHAPTER 4

PEMCC of grid-tied Wind – BESS is proposed that delivers DAC into the grid with rather smooth power and in cooperation with the grid operator. The proposed scheme proactively foresees resources' potential, estimates DAC, predictively assess resources, evaluate potential outcomes, and defines power injection into grid with rather fewer levels over 24h horizon. PEMCC then continuously communicates with grid and renews power injection levels to accommodate grid request. PEMCC can advance or delay power injection into the grid to deliver DAC and more if curtailment is evident. PEMCC provides:

- reduced wind energy curtailment
- predictive power injection level definition to supply rather smooth power into grid
- DAC delivery assurance
- grid support through on request power injection control every Δt
- reduced stress for the grid components due to rather smooth power injection

5.2 FUTURE WORK

Authors believe that PEMC algorithms with appropriate formulation can easily be extend and applied in scenarios other than those explored in this work. The followings should be explored in the future.

Off Grid PV (or Wind) Systems

PEMC in this work dealt with grid tied RE systems; however, PEMC over defined forecast horizon may play a role to minimize both power quality and supply and demand balance issues in off grid RE systems leading to better EMC.

BESS Size Optimization

In this work, PEMC was applied without BESS size optimization. Therefore, not only BESS size optimization is open for further examination, size reduction beyond the optimal size due to PEMC may also be attempted.

Off Grid Hybrid PV and Wind System

No attempts were made to apply PEMC to hybrid PV and wind system in this work. PEMC added with complimentary PV and wind systems may result in even better EMC.

BESS Life Extension

BESS life is defined by the number of charge/discharge cycles, and excessive charge/discharge cycles can result in a shorter BESS life. This work did not explicitly consider optimizing the number of charge/discharge cycles in PEMC. However, PEMC may be used to control and limit the number of charge/discharge cycles, with probability extending BESS life.

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