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Predictive energy management and control system for PV system connected to power electric grid with periodic load shedding

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ABSTRACT

Power Electric Grid (PEG) tied Photovoltaic (PV) plus Battery Energy Storage Stations (BESS) based Micro Grids (MG) are controlled and operated inefficiently with Conventional Energy Management and Control (CEMC) schemes. CEMC schemes, (1) leave these systems on the mercy of weather with either energy shortage resulting in loss of load (LOL) or requiring huge BESS resulting in high capital and Operation & Maintenance costs, (2) cause curtailment and thus wastage of surplus PV energy (PVE), and (3) increase energy cost due to unnecessary charging of BESS from PEG. LOL and surplus PVE wastage grow even further when MG are connected to a weak PEG with periodic load shedding.

This paper proposes predictive energy management and control system (PEMCS) for PV + BESS MG tied to a weak PEG with periodic load shedding. Twenty-four hours (24 h) forecasts of load demand and PV potential with PEG load shedding schedule and BESS status are used as decision variables. The proposed PEMCS reduces PV energy (PVE) wastage due to curtailment, increases PV proportion locally and into PEG for PEG support, decreases unnecessary charging from the PEG, and increases savings for owner-consumer. The proposed scheme is simple, effective, and realistic, and accounts for errors in the forecasts. Results show increased proportions of PVE for both consumers and PEG, energy cost saving for consumers, and enhances weak PEG operational reliability.

1. Introduction

Rising energy demand (International Energy Outlook, 2013) is rendering century-old existing Power Electric Grids (PEG), conventional generation sources and traditional control techniques insufficient to supply required energy reliably. Thus, PEGs are seeing integration of renewable energy (RE) systems on transmission as well as distribution levels (Syed and Raahemifar, 2014). A variety of RE technologies, such as wind and solar, have been integrated; however, only Photovoltaic (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 continue to decline, and requires inherently low maintenance that does not require a high level of technical skills or expertise (Syed and Raahemifar, 2015).

Micro Grid (MG), a type of RE system that operates both in parallel with the PEG and as standalone (SA) Mariam et al. (2013), is gaining popularity. In PEG grid tied (GT) mode, the minimum requirements for MG reliable operation are a source of generation (usually RE) and an operating PEG with stable voltage and frequency. However, energy storage (ES), usually a Battery Energy Storage Station (BESS) (and/or a fossil fuel generator (FFG)) is required for backup and reliable operation in SA mode. MG in GT mode supplies surplus energy into PEG and/or BESS when generation is greater than demand and retrieves from PEG and/or BESS when demand is greater than generation. Similarly, MG in SA mode uses energy generated and/or stored in BESS (and/or FFG) to supply for the load. Energy supply is even more important in SA mode since PEG will not be available, either due to unplanned failure or planned periodic load shedding (LS). However, the capability of MG to exploit available RE resources in SA mode when PEG fails is limited by the capacity of the BESS and load demand, which results in RE curtailment (Mai et al., 2012). Curtailment wastes the freely available RE and the amount of curtailment increases dramatically for MG tied to a weak PEG with LS. Unplanned LS may arise due to faults, loss of generation, switching errors, and lightning strikes (Shokooh et al., 2011), while planned LS may be due to PEG maintenance or insufficient generation. Unplanned LS caused by faults are unpredictable and sporadic, while planned LS are either infrequent and predictable for maintenance or planned and periodic due to insufficient generation.

Predictive Control (PC) has been reported for improving the power system stability (Sebaa et al., 2012) and controlling the

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emergency voltage (Larsson, 2004). PC has been proposed for controlling the frequency of power system (Ersdal et al., 2013) and for decentralized load frequency control in tough situations (Morattab et al., 2011). PC based mitigation of cascaded failures is discussed in Talukdar et al. (2005) and two-stage solution to prevent voltage collapse is discussed in Gong and Hiskens (2008). Thermal load overload alleviation using PC is reported in Otomega et al. (2007), and predictive energy management and control system (PEMCS) based dynamic energy management of RE integrated power systems are reported in Falahi et al. (2013). Power electronic systems PC is discussed in Geyer et al. (2005) and PEMCS based dynamic resources allocation in Zhang and Xia (2011). PC/PEMCS application has been discussed for load shedding in power distribution in power systems (Ghorbani et al., 2014), voltage stability during load shedding (Hiskens and Gong, 2005), and non-disruptive load shedding (Xue and Hiskens, 2012). PC/PEMCS approach has been used for operation optimization of MG (Parisio et al., 2014) and wind-battery MG (Han et al., 2013). However, none of the aforementioned studies has reported using PC or PEMCS to ensure energy supply for local load, minimize curtailment, increase PVE proportions in the grid, and support weak PEG with planned periodic LS.

PV + BESS MG is chosen since: (1) PV technology is the ideal candidate for these types of applications (Syed and Raahemifar, 2015), (2) Islamabad, Pakistan, has great PV potential, with a global horizontal irradiation (GHI) of 1860 kW h/m^2 at zero degree tilt and global incident at collector plane (GICP) of 2140 kW h/m^2 per year at 30° tilt due south system (PVSYST), (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), though it has also been employed on large scales (>MW). The Zinc Hybrid Cathode (Znyth) technology BESS was selected due to its low cost, low maintenance requirements, high energy density, high number of cycles, high depth of discharge (DOD), and high efficiency (eosenergystorage, 2014).

This paper proposes PEMCS for PV + BESS MG to minimize curtailment and thus increase PV proportions in a weak PEG with planned periodic LS to increase its energy supply reliability. Specifically, PEMCS achieves: (a) energy supply assurance in LS period (LSP), (b) increased PVE for consumer, (c) increased PEG reliability through higher PVE proportions into PEG due to lower curtailment, and (d) consumer cost savings through lower energy consumption from PEG, collectively called 4-goals in this paper. The proposed PEMCS is based on forecasted PV potential and load profile with utility periodic LS schedule over 24 hours (h) horizon in the future. Water And Power Development Authority (WAPDA) Pakistan, a weak PEG with periodic LS, is used as an example (Shah et al., 2011) to show the effectiveness of the proposed PEMCS. PV and load forecasting, and BESS size/cost optimization are outside the scope of this paper and interested readers are referred to (Photovoltaic and Solar Forecasting: State of the Art, 2013; Pandian et al., 2006; Campbell and Adamson, 2006; Hossain and Iqbal, 2014; Carpinelli et al., 2014). The rest of the paper is organized in the following sections: (2) Utility load shading profile, (3) PEG tied PV + BESS system, (4) PEMCS, (5) PEMCS formulation and algorithm, (6) Simulation, results, and discussion, and (7) Conclusions.

2. Utility load shedding profile

Fifty percent of Pakistan has access to electricity. The total installed capacity is 20 GW with a shortage of 6 GW (Shah et al., 2011). Six GW translates into approximately 5–6 h 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 period (LSP) of 2–4 h per day. Hence, residential, commercial and industrial sectors have relied on FFGs to continue to function. However, due to the higher cost of fossil fuel, promising PV potential (PVSYST), incentive for PV technologies, and recent Net-Metering (NM) rules (RE Policy for Development of Power Generation, 2006), Pakistan is poised for installing PV and PV + BESS at residential, commercial and industrial levels.

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

3. PEG tied PV + BESS system

Eq. (1) can be used to size BESS, where, E_{BESS} is BESS energy, E_D is LSP demand, DOD is depth of discharge, and η is BESS round trip efficiency.

$$E_{BESS} = E_D/(DOD * \eta) \tag{1}$$

Required BESS equals 40 kW h/day, to ensure energy supply during 3 h LSP (11 AM–2 PM), for a facility of a peak load E_D of 30 kW h (10 kW × 3 h LSP), with BESS DOD of 80% and η of 95%. DOD of 80% is chosen to extend the life of BESS battery (Carpinelli et al., 2014). The required PV system size (PV_{size}) is estimated by Eq. (2) and is approximately 7 kW. The peak sun hours (PSH) is given by Eq. (3) and equals 5.86 for Islamabad, Pakistan, with yearly GICP of 2140 kW h/m^2.

$$PV_{size} = E_{BESS}/PSH \tag{2}$$

$$PSH = GCIP/365 = 5.86 \tag{3}$$

However, an oversize PV system is required to ensure sufficient supply in all conditions including: (1) in winter with shorter periods of sun during a day ($PSH_{Dec} \leqslant 1/3–1/2$ of PSH_{Jun}) (PVSYST), (2) on cloudy/rainy days, and (3) with PV systems 20% conversion loss (de-rate factor, D_f = 80% to account for losses due to light, soiling, electrical, etc.). Using Eq. (4) the PV system is resized to be 12 kW. BESS size, can also be increased, if autonomy or backup for more than one LSP is required.

$$PV_{size} = (E_{BESS}/PSH)/(\eta * D_f) \tag{4}$$

The PVE yield of such a system is given by Eq. (5) and equals to 20.54 MW h/year. However, the maximum energy required during LSP per year is 11.6 MW h (40 kW h/day × 365 days' × 0.8), translating to a surplus of around 8.86 MW h of energy per year. With