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An optimal management strategy for distributed storages in distribution networks with high penetrations of PV

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ABSTRACT

This paper presents an innovative management strategy for distributed battery storages that greatly increases the capability of distribution networks to absorb and utilize photovoltaic (PV) generation. Optimal daily energy profiles for each storage unit are calculated using a Fourier series description based on one day ahead energy forecasts. Each battery charge/discharge profile is optimized to minimize a cost function that includes network and battery losses, battery cyclic costs and the network voltage profile. The optimization method combined an interior-point algorithm and pattern search algorithm. Simulations are carried out on a three-phase distribution system over a period of 24 h at 15 min interval with time varying loads. The adopted technique in this paper shows significant control abilities in peak shaving and load leveling. Results also indicate that proposed approach can enhance the performance of the grid by improving the voltage stability and reducing distribution losses thus providing the required security for consumers. Results also illustrate capacity and charging/discharging rates of batteries highly depend on the location of the controlled consumer battery and amount of controlled batteries.

1. Introduction

The global base of installed PV surpassed 100 GW in 2012 [1]. While PV generation offers economic and environmental benefits, the grid has a limited capability to accept PV energy. This is especially true in the low voltage (LV) distribution network where residential and smaller commercial arrays are connected. The technical difficulties include reverse power flow, over voltage, unbalance and neutral phase shifting. As the penetration level increases mainly during light load conditions at peak PV generation hours, the voltage at the PCC will raise. Consequently, the voltage drop along the feeder will be reduced and power flow is now reversed [2,3]. This is a condition not normally anticipated by the existing utility grids and can cause over voltage tripping at the inverter and network protection and other equipment affecting the performance of the grid. In order to accommodate high penetration levels, networks will have to undergo upgrades or alterations or alternative voltage control equipment may be required. Existing utility grids, even without the influence of distributed generation (DG) experience issues such as voltage sags and unbalance as a result of increasing demand [4,5].

The optimal integration of DG focuses on the solution of the consequent network problems. Ref. [6] develop reactive power control techniques to manage voltage violations while [7] evaluates optimal size and placement of DG to minimize network losses and cost of energy. However, these techniques may not be practical for wide spread installations of PV as the size and location of domestic PV units often depends on customer choice. The real challenge is to manage distributed PV to operate in parallel with the grid actively. Ref. [8] identifies the need for development of effective control mechanisms for loads, sustainable management of DG and sizing of energy storage. The Australian Federal Government Energy White Paper establishes that 25% of retail electricity costs are derived from peak events that occur over a period of less than 40 h per year [9]. Therefore adequate demand management strategies will need to be put in place to coordinate available energy sources to reduce the overall peak demand. Scheduling of large scale generation units can be done with minimal error as aggregated demands are highly predictable. However, the co-ordinated management of large numbers of distributed PVs and storages in the low voltage distribution network has received little attention.

This paper proposes a novel power dispatch control mechanism for distribution systems with large penetrations of PV for optimal real and reactive power flow management (OPF). Distributed battery storage devices, under the control of the network operator, are co-located with customer PV to allow the requisite degrees of

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Nomenclature

a_m	Fourier cosine coefficients
b_m	Fourier sine coefficients
BatteryCost	battery cost ($)
BatterySize	battery size (kWh)
BCC	battery capital cost ($/day)
BRC	battery replacement cost ($/day)
BUC	battery unit cost ($/kWh)
BWC	battery wear cost ($/day)
c_l	scaling factors
C_F	Fourier coefficients vector
C_{iF}	complete solution vector
C_{iT}	vector of battery energy at sample interval
CRF	capital recovery factor
Cycles	number of daily discharge–charge cycles
CycleLife	rated battery cycle life
D	number of battery operating days per year
DOD_{avg}	average daily depth of discharge
DOD_{max}	maximum depth of discharge (%)
E_B	battery energy (kWh)
$E_{B\text{-}act}$	actual battery capacity (kWh)
$E_{B\text{-}nom}$	nominal battery capacity (kWh)
E_B^{max}	maximum battery energy (kWh)
E_B^{min}	minimum battery energy (kWh)
f	cost function
f_l	individual cost components
i	bus number 1,2. . .*nbus*
I_B	battery current
I_k	branch current
i_r	interest rate
i_d	discount rate
J_l	value of optimized f_l
k	branch number connecting bus *i* and *j*
l	cost component number
m	Fourier coefficient number
n	number of samples ($T/\Delta t$)
nbat	number of batteries
nbus	number of buses
nbranch	number of branches
P_B	battery power (kW)
P_B^{min}	lower limit of battery power
P_B^{max}	upper limit of battery power
P_i	active power at PCC of bus *i*
P_{inv}	inverter active power (kW)
P_L	load active power at bus *i*
PCC	point of common coupling
Ploss	total power loss at *t*
P_s	solar power (kW)
PVlife	life of solar system (years)
q	battery real life (years)
Q_i	reactive power at PCC of bus *i*
Q_{inv}	inverter reactive power (kVar)
Q_L	load reactive power at bus *i*
r	resistive component of the impedance bus matrix
Rate	time of use utility rate
R_B	battery ramp rate
$R_{B\max}$	maximum ramp rate limit
S_{inv}	Inverter apparent power (kVA)
t	time
T	period
Δt	sampling interval
TBC	total battery cost ($)
V_{error}	total voltage error at *t*
V_i	voltage at bus *i*
V_2	positive sequence voltage
V_1	negative sequence voltage
V_t	battery terminal voltage
V_p	polarization voltage
V_{min}	lower limit of voltage
V_{max}	upper limit of voltage
VUF	total voltage unbalance at *t*
w_l	weighting factor
y	number of times battery need replacing
η_{chEff}	battery charging efficiency
η_{disEff}	battery discharging efficiency
η_{inveff}	inverter efficiency
θ	inverter power factor angle
ϕ	phase number
$Z_{c,d}$	charge/discharge impedance

freedom while making use of the available PV inverter capacity. This approach requires the active collaboration of the customer and utility. The optimization approach proposed applies equally well to network operated distributed community storages but these carry the cost penalty of providing dedicated inverters.

The proposed control approach focuses on optimal scheduling of the distributed storage for OPF while taking into account the utility operational requirements and constraints and battery costs. Benefits of proposed battery management strategy on the feeder include, reduced system losses, voltage profile improvement, load leveling, peak shaving and mitigation of effect of load and generation unbalances for unbalanced three phase feeders. A scheduling algorithm determines which generation unit (grid, PV or battery) operates at any given time interval and the charge/discharge mode of battery. Inverter interfaced batteries can operate either in real (P) or real and reactive (PQ) mode. Thus assists active management and allocation of available resources. Reactive power support was investigated by setting PV inverters to operate in constant power factor (PF) modes. Simulations were carried out for a three-phase four-wire unbalanced network using a hybrid interior-point algorithm [10] and pattern search algorithm in MATLAB [11].

2. System modeling

2.1. Battery storage

The paper proposes a battery charge/discharge management strategy for feeder quality enhancement considering the battery aging due to daily cycling. Performance of BESS depends on several internal and external parameters. Internal parameters like manufactured technology, design and material are usually uncontrollable and set by manufacturer. However, external parameters such as charge/discharge rates, linear state of charge and DOD are manageable. Typically they have larger impact on the battery cycle life and degradation [12,13].

Li-ion, NiMH, NiCd and lead acid batteries are few commonly known battery storage technologies. In contrast to other battery technologies, Li-ion batteries show excellent energy preservation capability with minimal internal power losses; high cycle life; low self-discharge rate and no hydrogen gassing [14]. As a result of this lithium-ion batteries are becoming increasingly popular [15].

Fig. 1(a) demonstrates the capacity and impedance as a function of cycling for a 12 V A123 ALM 12V7 lithium-ion battery rated at 4.6 Ah/10 A [14]. From the figure, at 1C/1C rate and 100% DOD the battery deliver more than 7000 cycles with excellent energy preservation capability.