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CO-ORDINATED CONTROL OF GRID CONNECTED PHOTOVOLTAIC REACTIVE POWER AND BATTERY ENERGY STORAGE SYSTEMS TO IMPROVE THE VOLTAGE PROFILE OF A RESIDENTIAL DISTRIBUTION FEEDER

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Abstract- The ever increasing energy demand, along with the necessity of cost reduction and higher reliability requirements, are driving the modern power systems towards distributed generation (DG) as an alternative to the expansion of the current energy distribution systems. In particular, small DG systems, typically with power levels ranging from 1 kW to 10 MW, located near the loads are gaining popularity due to their higher operating efficiencies. Photovoltaic cells (PV), Fuel cells (FC), Batteries, micro turbines, etc. are nowadays the most available DGs for generation of power mostly in peak times or in rural areas. It is desirable that the utilities ensure that the customers are supplied with a high power quality. Among the power quality parameters, voltage profile and Voltage Unbalance (VU) are the major concerns in low voltage (LV) distribution networks.
Voltage drop can be experienced in network peak hours while voltage rise can be experienced in network off–peak hours with high generation and penetration of DG units. The utilities are responsible for keeping the voltage in their network within the standard limits to prevent malfunction of customer devices.
Voltage unbalance is more common in individual customer loads due to phase load unbalances, especially where large single–phase power loads are used. Although voltages are well balanced at the supply side, the voltages at the customer ends can become unbalanced due to the unequal system impedances, unequal distribution of single–phase loads or large number of single–phase transformers. Usually, the electric utilities aim to distribute the residential loads equally among the three phases of distribution feeders.

Index Terms- —Battery energy storage (BES), distribution networks, droop control, photovoltaic (PV).

I. INTRODUCTION

The ever increasing energy demand, along with the necessity of cost reduction and higher reliability requirements, are driving the modern power systems towards distributed generation (DG) as an alternative to the expansion of the current energy distribution systems [1]. In particular, small DG systems, typically with power levels ranging from 1 kW to 10 MW, located near the loads are gaining popularity due to their higher operating efficiencies. Photovoltaic cells (PV), Fuel cells (FC), Batteries, micro turbines, etc. are nowadays the most available DGs for generation of power mostly in peak times or in rural areas [2]. It is desirable that the utilities ensure that the customers are supplied with a high power quality. Among the power quality parameters, voltage profile and Voltage Unbalance (VU) are the major concerns in low voltage (LV) distribution networks [3].

Voltage drop can be experienced in network peak hours while voltage rise can be experienced in network off–peak hours with high generation and penetration of DG units [3]. The utilities are responsible for keeping the voltage in their network within the standard limits to prevent malfunction of customer devices.

1.1 Decentralized Local Voltage Support of Low Voltage Distribution Networks with a New Control Strategy of PVs

In this the capability of PV converter to regulate the voltage of a specific load connected is investigated for voltage support in LV distribution networks. A decentralized local voltage support method is illustrated for a distribution network using the proposed operational strategy for the PVs installed by the householders. This method is capable of preventing voltage drop and voltage rise at network peak and off–peak periods, respectively.

Analysis

Let us assume a typical 3–phase radial balanced LV distribution feeder with 3– phase PVs installed as shown in Fig. 6.1. The rating and tap changing of distribution transformers and feeder cross–sections are designed in such a way that during normal operation conditions, the voltage profile is within the standard limits. However, practical measurements indicate that, a voltage drop to figures below the lower limit at network peak hours is frequent especially at the end of the feeders [85]. Network peak period is usually in the evening when PVs do not generate any active power. Therefore, voltage support by active power generation of PVs cannot be used.
At noon, the network is roughly in its off–peak load condition while the PVs generate their maximum active power. This results in voltage rise along the feeder.

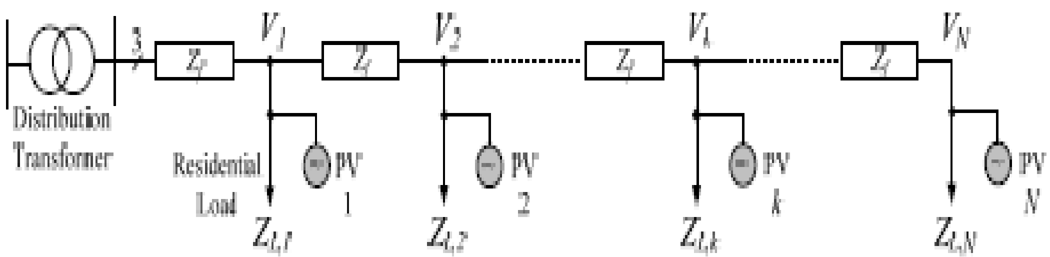

Fig. 1.1 Single line diagram of the LV distribution network under consideration

Consider the system shown in Fig. 6.2 in which *ES* and *ZF* are the Thevenin equivalents looking at the left of Point of Common Coupling (PCC). It is assumed that a PV and a load *ZL* are connected at the PCC bus. From this figure, we have

$$E_{PCC} = \frac{Z_L}{Z_F + Z_L}\left(E_S + Z_F I_{PV}\right)$$

……………………………….1.1

In (1.1), *EPCC* has a higher value when *IPV* > 0 than when *IPV* = 0. *EPCC* can be also greater than *ES* if *IPV* > *ES* / *ZL*. This shows how PVs can result in voltage rise in the network. For keeping the network voltage below an upper limit (i.e. *EPCC* ≤ α.*ES* where α ≤ 1.1) then acceptable range of PV output current is

$$I_{PV} \le E_S\left(\frac{\alpha}{Z_L} + \frac{\alpha - 1}{Z_F}\right)$$

……………………………….1.2

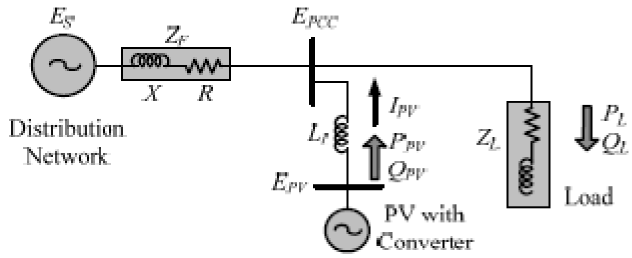

Fig.1.2 Circuital representation of a distribution network, load and PV.

Based on this concept, in [12] it was shown that voltage rise in a typical distribution feeder is greater at the end of the feeder and if the PV has a higher rating. In Fig. 1.2, let us assume $P = PPV – PL$ and $Q = QPV – QL$ and ΔV is the voltage difference between beginning of feeder (*ES*) and PCC voltage (*EPCC*) then

$$\Delta V = \frac{PR + QX}{E_{PCC}} \quad \text{.................................1.3}$$

During the off–peak period at noon, let us assume that *PL* and *QL* are constant but low, while the PV is working in UPF (*QPV* = 0). Let the PV be injecting such an amount of active power (*PPV*) that *EPCC* is equal to its maximum limit (=1.1×*ES*). Now, if based on MPPT, the PV starts to increase its injected active power by ΔP, ΔV will rise. In this situation, *EPCC* can be kept constant only if ΔV remains constant by making the PV to absorb some reactive power (*QPV*) without operating in UPF. This amount of reactive power is

$$Q_{PV} = -\Delta P \frac{R}{X} \quad \text{.................................1.4}$$

This required amount of reactive power is dependent on the feeder *R*/*X* ratio. In the evening, at the peak load period, the PV cannot inject active power (*PPV* = 0). Let us assume *PL* and *QL* are such that the PCC voltage drops to its minimum acceptable limit (=0.94×*ES*). If *PL* and *QL* now increase by ΔP and ΔQ, respectively, the PCC voltage will fall below the acceptable limit. This can be solved through reactive power injection at PCC. The required reactive power to be injected is

$$Q_{PV} = \Delta P \frac{R}{X} + \Delta Q \quad \text{.................................1.5}$$

Comparing (1.4) and (1.5), it can be seen that more reactive power exchange is needed for voltage drop improvement than voltage rise reduction for the same amount of ΔP change

1.1.1 PV Control strategies

As shown by (1.4) and (1.5), the PVs are capable of regulating their PCC voltage and prevent voltage rise or drop in the feeder. A PV can be operated in any of the three following strategies:

• Strategy 1: UPF strategy
• Strategy 2: Constant PQ strategy
• Strategy 3: Voltage Control strategy

The schematic diagrams of these strategies are shown in Fig. 1.3(a) while their detailed control block diagrams are shown in Fig. 1.4.

1.1.2 Strategy–1: UPF strategy

In this strategy, the PV regulates its output voltage such that the MPPT or APC generated active power flows into PCC in UPF. Let us consider the single–line diagram shown in Fig. 1.2. Let the PCC voltage magnitude and angle respectively be $|E_{PCC}|$ and δ_{PCC}. Let us assume that the PV is required to inject active power $P_{PV,ref}$, while reactive power is $Q_{PV,ref} = 0$. From Fig. 1.2, the power flow equations between the PV and PCC is

$$P_{PV,ref} = \frac{|E_{PV}| \times |E_{PCC}|}{\omega L_1} \sin(\delta_{PV} - \delta_{PCC})$$

$$Q_{PV,ref} = \frac{|E_{PCC}|}{\omega L_1} \left(|E_{PV}| \cos(\delta_{PV} - \delta_{PCC}) - |E_{PCC}| \right) \quad \text{……………………………….1.6}$$

where $L1$ is the filter inductance in the output of PV converter. From above equations $|E_{PV}|$ and δ_{PV} can be calculated for any reference value of PV active power and the PCC voltage

1.1.3 Strategy–3: Voltage control strategy

The general approach for this strategy is based on fixing the PCC voltage of each PV along the feeder to a desired value. The desired values of each node are based on a voltage droop line. A PV, while the sun is shining can act as a power source. However during the evenings, the converter and capacitor connected at the output of the PV can act as a Distribution Static Compensator (DSTATCOM). For this purpose, in the distribution feeder of Fig. 1.1with *n* nodes each with a 3–phase PV installed, each PV will fix its PCC voltage to the assigned value by the droop controller by injecting or absorbing the required amount of reactive power ($Q_{PV,ref}$).
Two major ideas for defining $Q_{PV,ref}$ are based on:
• Minimization PCC reactive power flow from grid
• Minimization PCC voltage error
In the first idea, each PV will try to generate the reactive power requirement of the load connected to that PCC, i.e.
PV ref L Q = Q , ……………………………….1.7
This will improve the power factor at each PCC to unity. For the second idea, $Q_{PV,ref}$ is calculated based on the difference between PCC actual voltage and the voltage reference as
PV ref (*PCC ref PCC*) *Q = m V −V* , , ……………………………….1.8
where *m* is a coefficient. This is shown in Fig. 1.3(b). For both of these methods, the PV converter must be capable of injecting/absorbing the calculated reactive power in (1.7) or (1.8). Therefore, at each time, this value must be in the acceptable range of 2 2 , ,max 2 2
PV ,max *PV PV ref PV PV − S − P ≤ Q ≤ S − P*……………………………… 1.9
For the second method, the PVs sometimes need to inject large amount of reactive power, which may result in large reverse reactive power flow into the distribution transformer (Q_{Feeder}). This may cause increased power loss in the network. To prevent this, a feedback from the Q_{Feeder} will be added to Q_{ref} in the case $Q_{Feeder} < 0$. This limits the reverse reactive power flow back to the distribution transformer.
The PV active power reference ($P_{PV,ref}$) is already defined from MPPT for day times or adjusted by APC controller and is equal to zero when the PV is not generating any active power in the evening or at night during

DSTATCOM mode of operation. *PPV,ref* will be controlled by the appropriate angle control of converter output capacitor (δ*cf*) [3]

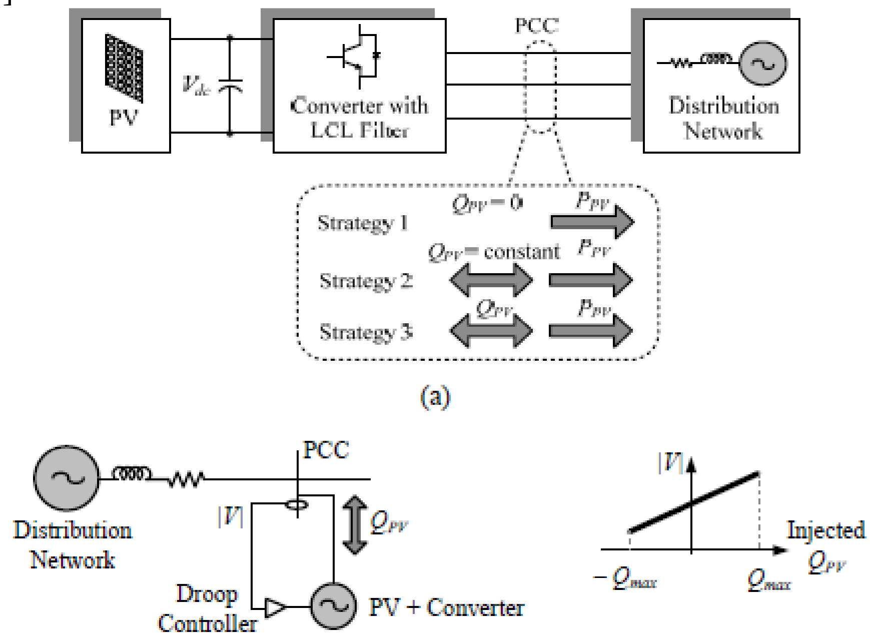

Fig. 1.3 (a) Power–flow–based system modeling, (b) General approach and droop–based controller

The installed capacity of embedded rooftop photovoltaic (PV) generation in residential distribution systems is rising rapidly worldwide [7], driven by reductions in costs, increases in electricity prices, and higher sensitivity about sustainability. Under the premise that this exponential trend will continue unabated, power distribution utilities must ensure that the quality of service to their customers will not be compromised [9]. For instance, the increased penetration of distributed PV sources has been cause of concern for harmonic pollution, but this issue can be resolved with standardization regarding harmonic distortion limits and the use of appropriate power electronic topologies.

II. VOLTAGE REGULATION REQUIREMENTS

The basic function of voltage regulation in a distribution system is to provide the system with steady-state voltage within an acceptable range at all times. Since the load on a feeder varies, utilities have the responsibility to regulate the service voltage supplied to customers within acceptable limits. In North America, most utilities follow the ANSI C84.1 guideline, which is shown in Figure 1. This guideline specifies utilization voltage, referring to voltage at the line terminals of equipment, and service voltage, referring to voltage at the point where the electrical system of the supplier and the electrical system of the user are connected. Furthermore, Range A is recommended for normal operating conditions, and Range B corresponds to unusual operating conditions.

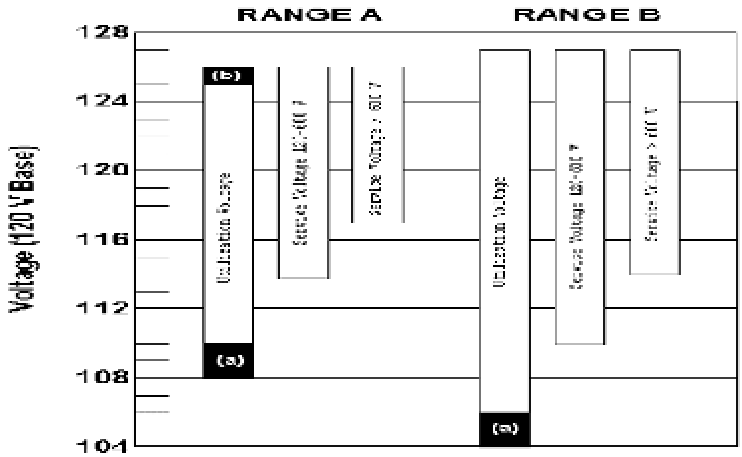

Fig.2.1. ANSI C84.1 Voltage Standards for 120-Volt System [5]

2.1 Voltage Regulation Methods

A typical distribution system with a primary feeder loaded along its length leads to a voltage drop due to the product of impedance and the total line current. Figure 2.1 shows a typical example of voltage ranges for primary feeder and secondary customer service points. Since the service voltage should be maintained within the ANSI C84.1 standard and power flow is unidirectional from the substation to the customer, there are two fundamental ways to regulate the voltage: either by using an on-load tap-changing transformer or by installing capacitor banks.

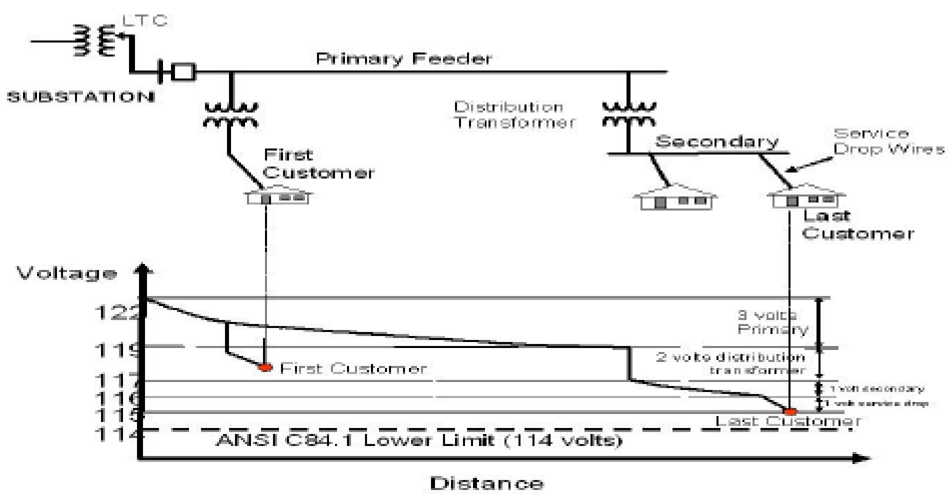

Fig.2.2 Typical Distribution Primary Feeder and Customer Voltage Ranges [6]

The tap changer works with a line-drop compensator circuit, as shown in Figure 3. This is set to compensate for the voltage drop between the regulator and the load center. For short period voltage variations outside of the predetermined bandwidth, a time delay is introduced into the circuit to prevent excessive operation of the tap changer.

2.2 Photovoltaic Inverter Reactive Power Support

With recent smart grid deployment, high importance has been placed on creating a reliable grid-level communication infrastructure that will enable real-time monitoring and control of a distribution system [13]. This would provide a distribution system with the capability of improving overall system efficiency by employing an Integrated Volt/VAR Control (IVVC) scheme and demand response programs. Even though the IVVC management system can provide promising loss-reduction benefits, installing capacitor banks in the system might increase power quality issues because of their transient and resonance characteristics. Therefore, managing reactive power from installed renewable-based DG sources would help to minimize voltage fluctuations caused by the varying nature and possibly reduce power losses [14]–[15]. Yan and Saha demonstrated that voltage instability can effectively be solved by PV inverter reactive power support [14]. Rizy et al., from the Oak Ridge National Laboratory, developed and tested a real

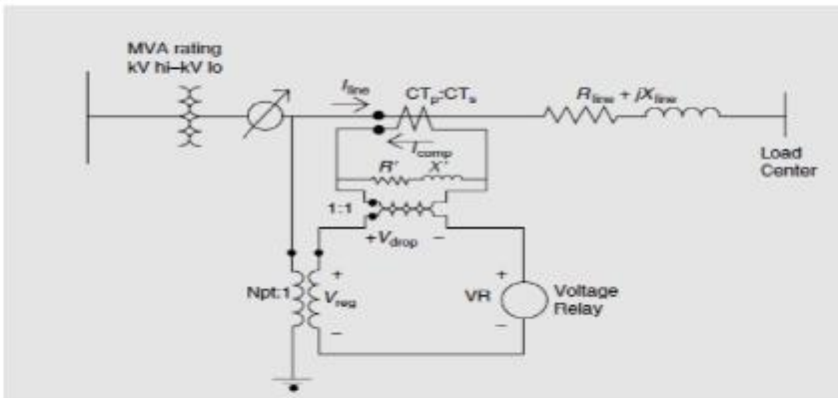

Fig.2.3 Line-Drop Compensator Circuit [7]

2.3 Distribution System Voltage Control

Distribution system voltage control is sometimes referred to as volt/var control (VVC), which Grainger and Civanlar (1985) specify as follows: The objective is to minimize the peak power and energy losses while keeping the voltage within specified limits for a variety of nominal load patterns. This objective is formulated as an optimization problem that is solved off-line, based on nominal load patterns. The optimization variables are the locations, sizes and control dead bands of capacitors and tap changer voltage regulators. Tap changers are normally automatically controlled by a relay controller that measures and regulates the secondary side voltage of the transformer. The control of transformers operating in parallel in the same substation must be coordinated to minimize circulating reactive power flows (Lakervi and Holmes, 1989

2.4 Preventive and Emergency State Voltage Control

The operation of power systems can be divided into the states normal, alert or emergency (Kundur, 1994). The system normally operates in the normal state, but enters the alert state if the system cannot be expected to be robust to the contingencies that have been considered in the design of the system. Such situations may occur for example due to unexpected load increase or outage of some component, such that a single contingency may force the system into the emergency state. The system enters the emergency state if a severe enough contingency occurs, so that the system will experience instability or exceeds operational limits unless emergency control actions are taken. However, the system is still synchronized in the emergency state.

2.5 Elements of the System that Produces and absorbs Reactive Power

Loads- a typical load bus supplied by a power system is composed of a large number of devices. The composition changes depending on the day, season and weather conditions. The composite characteristics are normally such that a load bus absorbs reactive power. Both active and reactive powers of the composite loads

2.6 Ways of Improving Voltage profile

Reactive power compensation is often most effective way to improve both power transfer capability and voltage stability. The control of voltage levels is accomplished by controlling the production, absorption and flow of reactive power. The generating units provide the basic means of voltage control, because the automatic voltage regulators control field excitation to maintain scheduled voltage level at the terminals of the generators. To control voltage throughout the system we have to use addition devices to compensate reactive power . Reactive compensation can be divided into series and shunt compensation. It can be also divided into active and passive compensation. But mostly consideration will be focused on shunt capacitor banks, static var compensator (SVC) and Static Synchronous Compensators (STATCOM), which are the part of group of active compensators called Flexible AC Transmission Systems (FACTS). The devices used for these purposes may be classified as follows:

- Shunt capacitors
- Series capacitors
- Shunt reactors
- Synchronous condensers
- SVC
- STATCOM

2.6.1 Shunt Capacitors

Shunt capacitors and reactors and series capacitors provide passive compensation. They are either permanently connected to the transmission and distribution system or switched. They contribute to voltage control by modifying the network characteristics. Synchronous condensers, SVC and STATCOM provide active compensation [15]. The voltages of the buses to which they are connected. Together with the generating units, they establish voltages at specific points in the system. Voltages at other locations in the system are determined by active and reactive power flows through various elements, including the passive compensating devices [16]. The primary purposes of transmission system shunt compensation near load areas are voltage control and load stabilization. Mechanically switched shunt capacitor banks are installed at major substations in load areas for producing reactive power and keeping voltage within required limits. For voltage stability shunt capacitor banks are very useful in allowing nearby generators to operate near unity power factor. This maximizes fast acting reactive reserve. Compared to SVCs, mechanically switched capacitor banks have the advantage of much lower cost. Switching speeds can be quite fast. Current limiting reactors are used to minimize switching transients. There are several disadvantages to mechanically switched capacitors. For voltage emergencies the shortcoming of shunt capacitor banks is that the reactive power output drops with the voltage squared. For transient voltage instability the switching may not be fast enough to prevent induction motor stalling. Precise and rapid control of voltage is not possible. Like inductors, capacitor banks are discrete devices, but they are often configured with several steps to provide a limited amount of variable control. If voltage collapse results in a system, the stable parts of the system may experience damaging over voltages immediately following separation. Shunt capacitors banks are always connected to the bus rather than to the line. They are connected either directly to the high voltage bus or to the tertiary winding of the main transformer. Shunt capacitor banks are breaker-switched either automatically by a voltage relays or manually [17]. Figure 2.1 shows example of capacitor bank. vary due to voltage magnitudes. Loads at low-lagging power factors cause excessive voltage drops in the transmission network. Industrial consumers are charged for reactive power and this convinces them to improve the load power factor.

Underground cables- they are always loaded below their natural loads, and hence generate reactive power under all operating conditions

Overhead lines- depending on the load current either absorb or supply reactive power. At loads below the natural load, the lines produce net reactive power; on the contrary, at loads above natural load lines absorb reactive power.

III. SYSTEM DEVELOPMENT

Increasing penetration of photovoltaic (PV), as well as increasing peak load demand, has resulted in poor voltage profile for some residential distribution networks. This report proposes coordinated use of PV and battery energy storage (BES) to address voltage rise and/or dip problems. The reactive capability of PV inverter combined with droop-based BES system is evaluated for rural and urban scenarios (having different R/X ratios). Results show that reactive compensation from PV inverters alone is sufficient to maintain acceptable voltage profile in an urban scenario (low-resistance feeder), whereas coordinated PV and BES support is required for the rural scenario (high-resistance feeder). Constant, as well as variable, droop-based BES schemes are analyzed. The required BES sizing and associated cost to maintain the acceptable voltage profile under both schemes is presented. Uncertainties in PV generation and load are considered, with probabilistic estimation of PV generation and randomness in load modeled to characterize the effective utilization of BES. Actual PV generation data and distribution system network data are used to verify the efficacy of the proposed method.

3.1photovoltaic inverter capacities for generating reactive power

Photovoltaic inverters are capable to generate reactive power [17]. Injection of generated reactive power into the grid can improve voltage profile and power factor of system. Inverters have a specified capacity so the maximum current of them is limit. This capacity can be used for generating active or reactive current by independent control of active and reactive current. Figure 1 shows the operational area for the current of photovoltaic inverter based on the limits. The blue circle in the Figure 1 represents the maximum rated current of photovoltaic inverter (*I*max,*R*) and the yellow circle displays the maximum overload current of photovoltaic inverter (*I*max). As photovoltaic modules are inflexible faced with overload current, the maximum active current of photovoltaic inverter (*Ipv*) is limited. So, the overload capacity can be used for generating reactive current. The red area in the Figure 1 illustrates the area of inverter current. The maximum apparent power of a photovoltaic inverter is specified. The active power generation capability of photovoltaic panels depends on the amount of radiation and varies during daytime. So, the maximum reactive power which can be generated is calculated by Equation (1) where t is time

$$Q_{\max}(t) = \sqrt{S_{\max}{}^2 - P(t)^2}$$

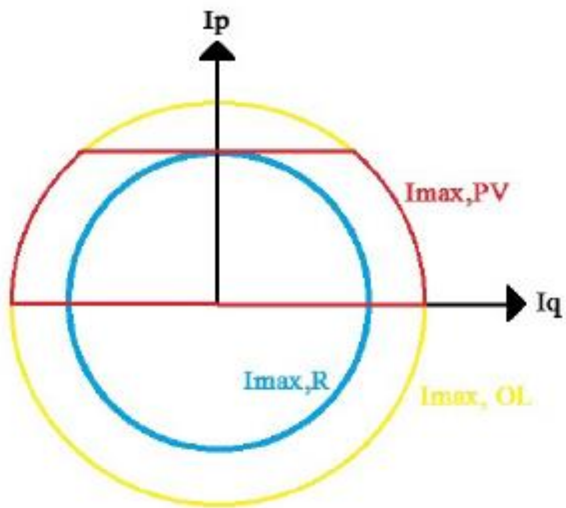

Fig3.1. Current area of photovoltaic inverter

3.2 Contributions

This report proposes a coordinated control of PV and BES system for voltage control of residential distribution systems. Unlike [21], [22], a local droop-based control of BES placed at each house is proposed and does not require advance metering infrastructures. In this report, integration of PV and BES in each house is similar to [20], except that BES charging and discharging is based on the house voltage. Coordinated inverter control is different compared to [24], as the primary aim is not to increase the active power injection from PV modules and make over-voltage problem worst. Another major contribution of this paper is the quantification of the impact of line characteristics on the effectiveness of reactive control, which has not been reported in the past. Although Carvalho et al. [16] have shown that the reactive control is effective for wide range of load and generation condition, its quantification with respect to R/X ratio of the line is missing. This quantification will determine the optimum BES sizing by utilizing the reactive capability of PV in combination with BES. Furthermore, modeling the effect of CT and partial shading using variability of PV as well as load is considered in this paper. Previously, Hollands and Huget [25] and Tiba et al. [26] have only included probabilistic modeling of clearness index and does not model it as "memory less" stochastic process. The net generation profile (difference between PV generation and load) can be considered as discrete time Markov chain (DTMC) process because the "future state" depends only on the "present state" and independent of the "past states." This paper discusses a detailed probabilistic modeling to find the effective utilization of BES under variable PV generation. Synopsis: In Section III, the coordinated control algorithm of PV and BES for voltage improvement is introduced. A sample LV system and extensive simulation results are presented in Section IV. The economics of the PV and BES systems is discussed in Section V highlighting the choices for battery selection and cost comparison. BES capacity utilization using variable generation and load

IV. CONCLUSION

This report introduces the use of coordinated control of PV inverters and droop-based BES to keep voltage in the acceptable range with high penetration of rooftop PVs in residential distribution systems. There may be over-voltage issues in the feeder due to the unity power factor real power injection from PV inverters in some residential feeders. Utilizing the reactive power capability of PV inverter is proposed to overcome this issue. However, from literature survey it is also found that when the line resistivity exceeds a certain critical value (this critical R/X ratio is 4.5–5 for the given network), reactive compensation alone becomes less effective. Therefore, the reactive capability of PV inverters alone is sufficient to improve the voltage profile in urban case,

where R/X ratio is close is unity, whereas droop-based BES combined with PV inverters are required in the rural case which has higher R/X ratio. If BES system were to be used alone for the voltage improvement, larger BES capacity is required.
Constant as well as variable droop-based BES schemes are investigated. Although both schemes show good performance, constant droop-based BES requires larger battery size and unequal investment in BES for the customers depending on their location in the feeder. Variable droop-based BES, however, requires smaller battery size and equal investment in BES from all the customers in distribution feeder. The proposed coordinated control algorithm alleviates both the over-voltage and the voltage dip problem in the residential feeders. Advantage of variable droop-based energy storage is discussed in terms of financial investment from customers and brief comparison of financial and technical advantages between BES and D-STATCOM (reactive power compensation device) is presented. Although one time investment in D-STATCOM is lower when compared with total investment in BES, BES provides long-term technical benefits in terms of peak shaving.

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