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UTILITY ENERGY SAVINGS BY NOVEL SMART INVERTER CONTROL OF PV SYSTEMS, BESS AND EV CHARGING STATIONS AS STATCOMS

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SUMMARY

This paper presents a novel technique of achieving energy savings in utility networks by simultaneous reduction of line losses and Conservation Voltage Reduction (CVR) on a 24/7 basis. This is achieved by a patented smart inverter control of PV systems, Battery Energy Storage Systems (BESS) and Electric Vehicle (EV) Charging Stations as dynamic reactive power compensator STATCOM. The PV systems provide reactive power with their entire inverter rating at night for STATCOM operation (PV-STATCOM). However, this reactive power control capability gets reduced during daytime. Meanwhile, the active power exchange of BESS and EV systems is much less than their inverter ratings during several periods during day thus making available a substantial amount of reactive power. This paper utilizes the combined reactive power capability offered by PV, BESS and EV stations over a 24/7 period for STATCOM operation to optimally control voltages in utility networks.

A modified version of IEEE 14 bus system is utilized for system studies. Sensitivity studies are utilized to reveal buses that are most suitable for reducing line losses through optimal voltage control. Different Distributed Energy Resources (DERs) i.e., PV systems, BESS and EV systems are connected at these buses both individually, and in different combinations for various studies. The total rating of DERs connected at buses 5, 7 and 14 are 12 MVA, 6 MVA and 10 MVA, respectively. The times series active power production data for PV systems, and power charging/discharging data for BESS are obtained from California ISO (CAISO). The EV data is estimated based on the number of charging stations in California, and the average power exchange data from a typical charging station. The system load is normalized according to the daily load in California for specific study days. Extensive Optimal Power Flow (OPF) studies using PSS/E are conducted at 15 minute interval for the following objective : Combined line loss reduction and CVR, for both individual DERs and different combinations of DERs connected at sensitive buses, for both sunny and cloudy days for PV; and both weekdays/weekends for BESS and EV. It is shown that the night and day optimal voltage control through STATCOM operation of the three types of DERs utilizing their combined reactive power capability can provide significant line loss reduction and energy savings for utilities.

KEYWORDS

Smart inverter, PV-STATCOM, BESS, Conservation Voltage Reduction, EV Charging Stations, Line Loss Reduction, Optimal Power Flow, DER, PV system, BESS

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I. INTRODUCTION

Global demand for electricity is expected to increase 50% by the year 2050 [1]. It is therefore important that while this demand gets supplied by various generating sources, expectedly from renewables, transmission and distribution line losses be minimized. Line losses are typically 4-5% in North American transmission and distribution systems [2]. Considering an average Ontario demand of 20,000 MW during daytime, the line losses are 800 MW. This line loss, if saved, can easily supply the power needs of almost half a million people. Hence, even a fractional reduction in line losses can have substantial benefits. It is noted that some other countries have line losses as high as 15-20 % [2].

Volt-Var control strategies involving voltage regulators, transformer taps, and switched capacitors are conventionally used in distribution systems for line loss reduction [3]. As per the revised IEEE 1547-2018 [4], Distributed Renewable Generators (DERs) can participate in voltage regulation. Recently some studies have shown the use of smart inverters with volt-var controls for line loss reduction. Volt-Var and Volt-Watt are the predominantly used smart inverter functions of DER for voltage regulation. Steady state reactive power compensation from Distributed Generators with combined rating of 2.5 MW has been shown to reduce line losses from 42.5 kW to 29.6 kW [5]. Varying the steady state voltage reference of 50 MW - 80 MW Distributed Generators in an Indian province reduced the line losses from 8.36 MW to 8.07 MW [6].

Peak load reduction and reduction of overall energy consumption in distribution system are beneficial for utilities, and they employ various methods to reduce them. Conservation Voltage Reduction (CVR) is an established technique to achieve above targets. Conservation Voltage Reduction (CVR) is the lowering of voltage on primary distribution networks with the goal of reducing the overall energy consumption and peak demand. CVR implementation in BPA [7], BC Hydro [8] and Hydro Quebec [9] has demonstrated that a voltage reduction by 1% resulted in energy savings of 0.3-1%. The application of Volt- Var control of smart inverter for CVR has been studied on Hawaiian Electric Companies Distribution System (HECO), which has a high PV penetration, a mix of underground and overhead cables, and partial residential and commercial loads [10]. With centralized Voltage optimization (VO) without smart inverters, the annual energy savings is increased by 1.505%. It is shown that energy savings can further increased by smart inverter control. 50% PV penetration with 100% smart inverter density increases annual energy savings by 2.05%, whereas 100% PV penetration with 100% smart inverter density increases energy savings by 2.88% [10]. In the distribution system of Pacific Gas and Electric Company (PG&E), smart PV inverter controls are shown to increase the annual energy savings to 4.30%, compared to 3.86% achieved by the VO method [10]. A combination of line loss reduction and CVR in the IEEE 14 bus system using smart inverters with Volt-Var control is shown to reduce active power demand by 2.11% leading to energy savings of 139.2 MWh/day [11].

From the above cases, it is evident that smart inverter control of DER can reduce annual energy consumption and line loss. However, the smart inverter controls, Volt-Var, and Volt-Watt, are not defined for nighttime [4], hence can be applied only during daytime. The Volt-Watt control requires curtailment of real power which may not be preferred as it leads to revenue loss for the PV system. Moreover, the PV system capability available for reactive power support is limited at noontime, when they generate maximum power.

The effects of PV-BESS systems on peak load shaving in a commercial building in Texas is reported in [12]. It is shown that a mix of PV-BESS systems with coordinated peak load shaving can help reduce loads on the grid and prolong the life of distribution equipment. A case study of the effects of PV-BESS systems on bus voltages levels in Jurong Port, Singapore is presented in [13]. Three load levels were tested (Light, Medium, and Heavy) and for each load level three cases were compared to the base case (PV vs PV-BESS charging vs PV-BESS discharging). The study concluded that the addition of PV and BESS improved the steady state voltages of the buses [13]. It is noted that Volt-Var control is not defined for nighttime [4], hence can only be applied during daytime.

Similar to PV system and BESS, Electric Vehicle charging stations can also participate in voltage regulation using remaining inverter capacity. With the increasing installations of EV charging stations, they can provide voltage regulation when PV and BESS capacity are limited due to active power production. To the best of authors' knowledge, smart inverter voltage control has not been implemented on EV either for line loss reduction or implementing CVR. Furthermore, the application of combination of BESS, PV system and EV are not reported in literature so far.

PV-STATCOM is a new smart inverter technology which controls the PV plant as a dynamic reactive power compensator STATCOM both during day and night [14]. The PV-STATCOM can provide several STATCOM functions, e.g. motor stabilization, power oscillation damping, etc. [15, 16].

This paper presents the application of combination of PV, BESS and EV as dynamic reactive power compensator PV-STATCOM, both during night and day for CVR and line loss reduction. During nighttime, the full PV inverter capacity is made available for STATCOM operation. However, the inverter capacity remaining after real power exchange is used for STATCOM operation in PV systems during daytime and in BESS, and EV system both during night and day.

This paper is organized as follows: The reactive power capabilities of various DER sources are presented in Section II, whereas the study system is described in Section III. The methodology used for the studies are presented in Section IV. The results of the studies are shown in Section V. Section VI concludes the paper.

II. REACTIVE POWER CAPABILITIES OF DER SOURCES

The active power output (P) and reactive power capability (Q) of a PV system over 24 hours for a sunny day, derived from CAISO data [17] is illustrated in Figure 1. The reactive power capability available for PV-STATCOM operation is calculated as per (1). During nighttime, full inverter capacity is available for reactive power production as active power production is zero. During noontime, when PV is producing is generating maximum active power, the inverter capacity available for reactive power production is zero. Thus, the PV plant is not able to provide reactive power support at noontime for CVR.

$$Q = \sqrt{S^2 - P^2} \tag{1}$$

where S is the MVA rating of the inverter.

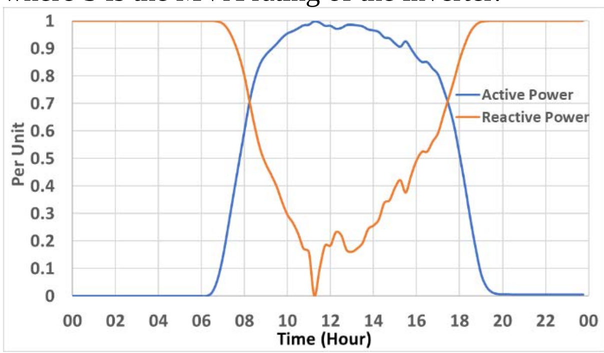

Figure 1. Active power output and reactive power capability of a PV solar farm for a sunny day

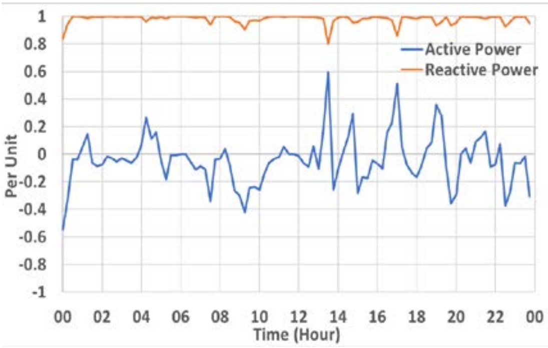

Figure 2. Active power output and reactive power capability of a BESS for a sunny day

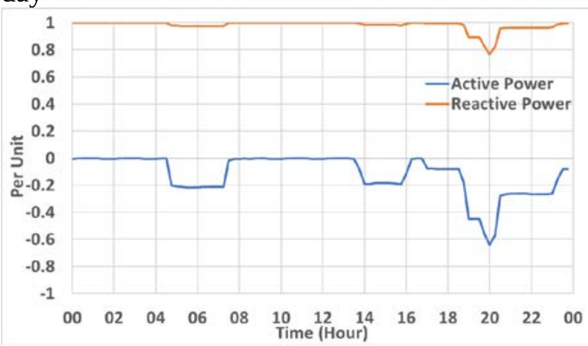

Figure 3. Active power output and reactive power capability of an EV for a weekday

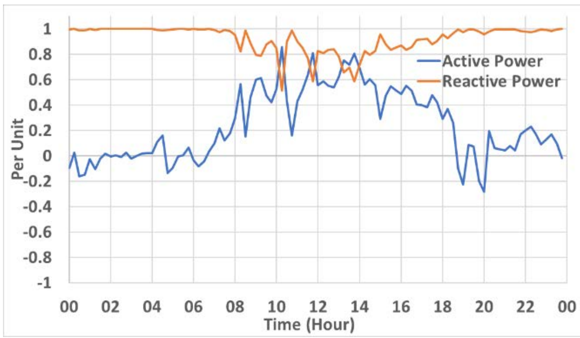

Figure 4. Active power output and reactive power capability of combination of PV, BESS, and EV in ratio of 40:30:30.

The active power output (P) of a BESS derived from CAISO data [17] is portrayed in Figure 2. The charging of BESS is considered as positive P, whereas discharging of BESS is considered as negative P. The remaining inverter capacity available for PV-STATCOM operation calculated according to (1) is also illustrated in Figure 2. The active power output of an EV charging station over 24 hours, estimated based on the number of charging stations in California, and the average power exchange data from a typical charging station [18] is depicted in Figure 3. The Q capability is also shown in Figure. 3. The EV charging occurs mostly in either nighttime, early morning or late evenings. Thus, EV has room for reactive power support during noontime, when PV is not available for voltage regulation. The discharging/charging of BESS is distributed throughout the day, and thus it can complement the reactive power capability of PV and EV. The active power output and reactive power capability of the combination of PV, BESS, and EV, in the 40:30:30 ratio, are depicted in Figure 4. Since the DERs complement each other in their capability for reactive production, it can be observed that a combination of DERs can provide reactive power support 24 hrs. This capability of the combination of DERs to provide reactive power support 24/7 opens new opportunities to use them for CVR and line loss reduction.

III. MODELLING OF STUDY SYSTEM

A modified version of IEEE 14 bus system [19] shown in Fig. 5 is utilized for system studies. It consists of two generators, three synchronous condensers, and 11 loads. The system voltage is 138 kV. The HV network is represented by an equivalent generator connected to bus 1. A fixed capacitor is connected to bus 9. Sensitivity studies reveal that buses 5, 7, and 14 are most suitable for reducing line losses through optimal voltage control. Different Distributed Energy Resources (DERs) i.e., PV, BESS, and EV are therefore connected at these buses both individually, and in different combinations for various studies. The rating of DERs connected to buses 5,7, and 14, are 12,6, and 10 MVA, respectively.

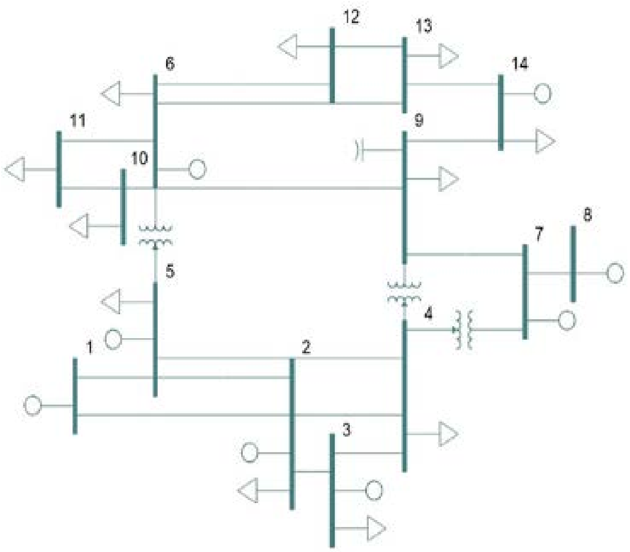

Figure 2. IEEE 14 bus system.

Modeling of DERs

For the Optimal Load Flow (OPF) studies, all the DERs (PV, BESS, and EV) are modeled as PV buses in PSS/E.

Modeling of Loads

The IEEE 14 bus system parameters are adopted from [19]. The system load is normalized according to the daily load in California for specific study days. The ZIP load model is used to represent different categories of loads. The impact of voltage on loads is quantified as a CVR factor which represents the change in load for a 1% change in voltage. The combined ZIP parameters [0.4, 0.3, 0.3] are used in studies that correspond to a CVR factor of 1.05 [20].

IV. METHODOLOGY

OPF studies for minimizing line losses are performed with the following variants of CVR:

1. Base Case: In this case, all DERs are operating at unity power factor (Q = 0).
2. CVR 1: In this case, the lower voltage limit is reduced from 1.0 pu to 0.98 for all buses, except the grid bus (Bus 1).
3. CVR 2: In this case, the grid bus voltage is reduced from 1.05 pu to 1.03 pu, and lower voltage limits are reduced from 1.0 pu to 0.

OPF studies are performed using the objective function of reducing line loss, including following equality and inequality constraints:
Minimize:

$$P_{loss} = \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} I_{ij}^2 * R_{ij}, \quad \text{where, } I_{ij} = \left(|V_i|\angle\delta_i - |V_j|\angle\delta_j\right) * |Y_{ij}|\angle\theta_{ij} \tag{2}$$

subject to,
Equality Constraints:

$$\begin{aligned} P_i = P_{Gi} - P_{Li} &= \sum_{j=1}^{N} \left|V_i V_j Y_{ij}\right| \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \\ Q_i = Q_{Gi} - Q_{Li} &= -\sum_{j=1}^{N} |V_i V_j Y_{ij}| \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \end{aligned} \tag{3}$$

Inequality Constraints:

$$\begin{aligned} V_i^{min} \leq V_i \leq V_i^{max} \\ \delta_{ij}^{min} \leq \delta_{ij} \leq \delta_{ij}^{max} \\ Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \end{aligned} \tag{4}$$

where, P_{loss} denotes the system active power loss. N is the total number of buses, V_i and V_j are respectively voltage magnitude of i^{th} and j^{th} bus. δ_i and δ_j are the voltage angles of i^{th} and j^{th} bus, respectively. I_{ij} is the current flowing from i^{th} bus to j^{th} bus. Y_{ij} and R_{ij} are respectively the admittance and resistance of line between i^{th} and j^{th} bus. P_i and Q_i are respectively the active and reactive power flowing out of i^{th} bus. PG_i and PL_i are respectively the active power generation and active power load at i^{th} bus. QG_i and QL_i are respectively the reactive power generation and reactive power load at i_{th} bus.

The equality constraints (3) are the power flow equations. The inequality constraints constitute of the limit on voltage magnitudes and voltage angles, and reactive power capacities of generators. The voltage constraints are set to 1.06 pu to 0.98 pu for all buses except grid (slack) bus for both CVR 1 and CVR 2. The grid voltage is set to 1.05 pu, and 1.03 pu, for CVR 1, and CVR 2, respectively. Q_{Gi}^{min} , and Q_{Gi}^{max} for PV, BESS, and EV are calculated using (1).

OPF studies using PSS/E software are performed at intervals of every 15 minutes over a 24 hour period for the following cases:

- *Case 1*: This case was comprised of PV, BESS, and EV components using CVR 1 with data taken from a sunny day. The ratio of these components was 40:30:30 for PV, BESS, and EV, respectively.
- *Case 2*: This case was comprised of PV and BESS components using CVR 1 with data taken from a sunny day. The ratio of these components was 100:60 for PV and BESS, respectively.
- *Case 3*: This case was comprised of PV and EV components using CVR 1 with data taken from a sunny day. The ratio of these components was 100:2 for PV and EV, respectively.
- *Case 4*: This case was comprised of exclusively PV using CVR 1 with data taken from a sunny day.
- *Case 5*: This case was comprised of PV, BESS, and EV components using CVR 2 with data taken from a sunny day. The ratio of these components was 40:30:30 for PV, BESS, and EV, respectively.
- *Case 6*: This case was comprised of PV and BESS components using CVR 2 with data taken from a sunny day. The ratio of these components was 100:60 for PV and BESS, respectively.
- *Case 7*: This case was comprised of PV and EV components using CVR 2 with data taken from a sunny day. The ratio of these components was 100:2 for PV and EV, respectively.
- *Case 8*: This case was comprised of exclusively PV using CVR 2 with data taken from a sunny day.

In addition to these eight cases, analysis was performed on multiple other combination of the three DERs, using both CVR 1 and CVR 2 for sunny and cloudy days. However, due to space constraints, only the above eight cases are described, which provided the best results.

In CVR 1, and CVR 2, DERs participate in CVR by providing reactive power support using available inverter capacity after active power production. The results of the CVR studies are compared with the base case in terms of reduction in energy demand and line losses, to evaluate the benefits of using DERs as STATCOM (similar to PV-STATCOM) for CVR and line loss reduction.

V. Reduction of Power Losses and Power Demand

Fig. 6 depicts the active power losses for the combination of PV, BESS, and EV during a sunny day scenario. It is observed that the largest reduction in active power losses results when CVR 1 is in effect, instead of CVR2. Also, the highest power loss reduction occurs during peak demand hours, which is quite beneficial for the distribution utility. Fig. 7 illustrates the utility network power demand for a combination of PV, BESS, and EV on a sunny day. The greatest reduction in power demand is achieved during peak load period, essentially leading to peak-shaving. In this study CVR2 caused the larger power demand reduction as compared to CVR 1, since the grid bus voltage is lower in CVR2. Furthermore, CVR2 reduces power demand throughout the day including non-peak load conditions.

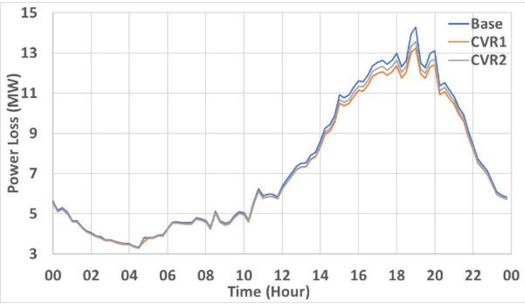

Figure 6: Active Power Losses for PV-BESS-EV combination on Sunny Day

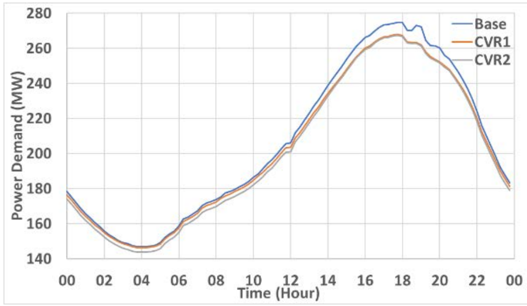

Figure 7: Power Losses for PV-BESS-EV combination on Sunny Day

VI. Variation of Bus Voltages

Figs. 8 (a) and (b) illustrate the voltages over a 24-hour period at different buses for the base case and CVR 2. The base case shows a large variation in bus voltages. However, these voltage variations are substantially reduced through CVR 2.

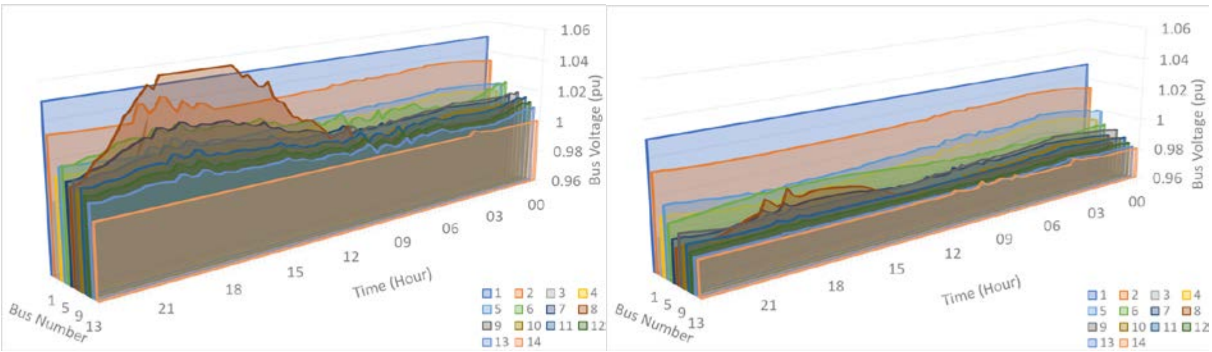

Figure 8: Variation of Bus Voltages, PV-BESS-EV, Sunny Day. (a) Base case, (b) CVR2

Table 1 presents both the reduction in power losses and power demand with different combinations of PV, BESS and EV for CVR 1 and CVR 2 – all on sunny days. It is observed that in either CVR scenario, a higher power loss reduction and a higher demand reduction is achieved as either BESS or EV is added to PV systems, making a higher availability of reactive power for optimal voltage control. The highest reduction in line losses and power demand is accomplished when all the three types of DERs i.e., PV, BESS and EV are combined together.

Table 1: Reductions in Power Loss and Power Demand compared to the base case

Case Study	Composition	Power Loss Reduction (%)	Power Demand Reduction (%)
Case 1	**PV-BESS-EV Sunny Day (CVR 1)**	2.41	1.43
Case 2	**PV-BESS Sunny Day (CVR 1)**	2.34	1.42
Case 3	**PV-EV Sunny Day (CVR 1)**	2.17	1.33
Case 4	**PV Sunny Day (CVR 1)**	1.94	1.22
Case 5	**PV-BESS-EV Sunny Day (CVR 2)**	1.96	2.47
Case 6	**PV-BESS Sunny Day (CVR 2)**	1.94	2.45
Case 7	**PV-EV Sunny Day (CVR 2)**	1.90	2.40
Case 8	**PV Sunny Day (CVR 2)**	1.65	2.29

The PV-BESS-EV combination results in maximum reduction in line losses for CVR1, but maximum reduction in power demand for CVR2. Since reduction in power demand is more important, CVR2 is seen to perform better than CVR1.

VII. FINANCIAL ANALYSIS

From Table 1, it is seen that it is more beneficial to focus on the reduction of power demand requirements rather than reduction of line losses. For reducing power demand, the PV-BESS-EV Sunny Day (CVR 2), is chosen as optimal as it has the highest reduction. This combination created energy savings of 124.12 MWh/day resulting in daily savings of $9,308.99 and yearly savings of $3,397,781.58. The 124.12 MWh reduction is equivalent to annual energy requirements of 4354 U.S. homes.

VIII. CONCLUSION

This paper presents a novel patented smart inverter control of a PV, BESS, and EV system as a STATCOM both during the day and night time to achieve CVR and line loss reduction simultaneously. Studies are performed on a modified IEEE 14 bus system. Extensive Optimal Power Flow (OPF) studies using PSS/E are conducted at 15 minute interval for two objectives: i) Minimizing line losses, and ii) Combined line loss reduction and CVR. The following conclusions were made:

- A combination of PV, BESS, and EV has a higher reactive power capability for smart inverter operation than PV alone
- The combination of PV, BESS, and EV has a higher capability of reducing power demand than PV alone.
- Both CVR 1 & CVR 2 reduce line losses during peak hours, however CVR 1 offer the greatest reduction
- Both CVR 1 and CVR 2 reduce power demand, especially during peak loading hours. CVR 2 provides reduction in power demand during off peak hours as well.

The proposed novel STATCOM control on the combination of PV, BESS and EV with CVR2 in the IEEE 14 bus system results in a saving of energy sufficient to power to 4354 U.S. homes. An implementation of this technique on a larger provincial or regional grid would result in substantially larger savings. With the rapid growth of PV, BESS and EV systems in utility networks, the proposed STATCOM control on these DERs can provide substantial energy savings for utilities both during night and day.

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