Energy Savings Estimation of a Distribution System in Presence of Intelligent Volt-VAr Control Based on IEEE Std. 1547-2018

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***Abstract*—In the present scenario, many solar photovoltaic (SPV) systems have been installed in the distribution network, most of them are operating at the unity power factor, which does not provide any reactive power support. In future distribution grids, there will be significant advances in operating strategies of SPV systems with the introduction of smart inverter functions. The new IEEE Std. 1547-2018 incorporates dynamic Volt/VAr control (VVC) for smart inverters. These smart inverters can inject or absorb reactive power and maintain voltages at points of common coupling (PCCs) based on local voltage measurements. With multiple inverter-interfaced SPV systems connected to the grid, it becomes a necessary task to develop local, distributed or hybrid VVC algorithms for maximization of energy savings. This paper aims to estimate substation energy savings through centralized and decentralized control of inverters of SPV system alongside various VVC devices. Control strategies of each SPV inverter have been accomplished in compliance with IEEE Std. 1547-2018. Time-series simulations are carried out on the modified IEEE-123 node test system. By utilizing smart inverters in traditional SPV systems, considerable energy savings can be obtained. These savings can be further increased by incorporating optimal intelligent VVC characteristics (IVVCC). Results show that just by allowing smart inverters on a predefined IVVCC (as per IEEE Std. 1547-2018), a reduction of 11.69% in reactive demand and 5.63% in active demand have been acquired when compared with a conventional SPV system. Reactive energy demand is additionally reduced to 48.42% by considering centralized control of VVC devices alongside optimal IVVCC.**

***Index Terms*—Conservation voltage reduction, IEEE Std. 1547-2018, smart inverter functions, solar photovoltaic system, Volt/VAr control, Volt/VAr optimization.**

NOMENCLATURE

$P^l_{i,t}/Q^l_{i,t}$	Real/Reactive power consumption of i^{th} node at time t.
G^{std}	Standard solar irradiance, i.e., 1000 W/m^2.
k_n^{Temp}	Temperature coefficient of PV-plate connected at nth node.
$T^c_{n,t}$	Cell temperature of nth PV generator over time t.
T	Reference cell temperature.
$V_m^{\min}$	Minimum allowable voltage at m^{th} node.
$V_m^{\max}$	Maximum allowable voltage at m^{th} node.
$V_{j,t}^{\text{vr}}$	Regulation ratio of j^{th} regulator at time t.
$TAP_{j,t}^{\text{VR}}$	Tap position of j^{th} regulator at time t.
ΔV_j	Voltage change per step of j^{th} regulator.
$P^r_{i,t}/Q^r_{i,t}$	Nominal real/reactive power of i^{th} node at time t.
$DATO_j$	Daily maximum allowable tap operations of j^{th} regulator.
$DASO_k$	Daily maximum allowable switching operations of k^{th} capacitor unit.
$Q_{k,t}^{\text{cap}}$	Reactive power supplied by k^{th} capacitor unit at time t.
$SW_{k,t}^{\text{cap}}$	Switch position of k^{th} capacitor at time t.
q_k^{cap}	Rated kVAr of k^{th} capacitor.
$V_{i,t}^a$	Actual complex voltage of i^{th} node at time t.
V_i^r	Nominal voltage of i^{th} node.
$P_{n,t}^{\text{pv}}$	Real power output of PV generator connected at node n over time t.
P_n^{rated}	Rated power capacity of PV connected at node n.
G_t	Solar irradiance over time t.

I. INTRODUCTION

IN a traditional distribution network, on-load tap changers (OLTCs), voltage regulators (VRs), and capacitor banks (CBs) are utilized to perform Volt/VAr optimization in order to achieve various objectives. Nowadays, many distributed energy resources (DERs) are integrated in a distribution grid. In 2012, global installed capacity of solar photovoltaic (SPV) was 100 GW, which crossed 390 GW by the end of 2017 [1]. Many distributed SPV systems are still operated with conventional inverters at unity power factor. These inverters can only supply active power to the grid. However, nowadays, SPV systems are increasingly paired with smart inverters, which can inject as well as absorb reactive power and control voltages at the PCC. These smart inverters have capabilities to make decisions based on local or distributed measurements (in terms of voltage, power factor, etc.). Earlier, DERs were not allowed to participate in voltage regulation. Thereafter, in 2014 an amendment was made in IEEE Std.1547-2003 to allow smart inverter-based generation to participate in voltage regulation [2]. Recently (2018), Std.1547-2003 is revised and certain operational constraints have been introduced for smart inverter based PV generators [3].

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In the future, there can be obligations for distribution utilities and DER operators to follow IEEE Std.1547-2018 to control voltages over the distribution system. Traditional volt-VAr optimization (VVO) formulation will significantly change with these additional sources and constraints. In this case, the VVO also needs to incorporate various smart inverter functions [4]. The smart inverter based Volt/VAr control can be included in the VVO formulation into two ways, i.e., based on local measurements, and based on distributed coordinated measurement. In local measurement-based control, the DERs (through the smart inverter) can supply or absorb real (P) and reactive (Q) power according to a local feedback signal, e.g. voltage, power factor (PF), etc. Real and reactive power can be supplied or absorbed based on the feedback signal received from the centralized control system. In the method based on centralized control, utilities performs an optimization to achieve a set of objectives to issue a control command to the smart inverters.

In the past, a few researchers have worked on the VVO by considering renewable energy sources (RES) in the distribution grid. The overview literature in this domain has been compiled in Table I. In [6], [7], real and reactive power of wind farms are considered as control variables with the real power of other RES. Whereas, only real power has been taken as a control variable in [5], [8], [9]. A few studies [10]–[12], have also utilized converter capability to control reactive power. Dispatchable DGs are considered in [13], where both power factor and active power have been taken as control variables. Thereafter, power factor based reactive power control of SPV and WT generators has been studied in [14]–[17].

In the literature, very few studies have considered SPV systems operating with smart inverters [18]–[21]. The full reactive power capability of a smart inverter has been utilized in [18]. In [19], the reactive power support of a SPV system is considered, where the reactive power (Q) capability of an inverter is determined based on maximum power point tracking (MPPT) and power factor. Thereafter, the scheduling of reactive power has been obtained within the obtained capability. In [20], the reactive power priority of a smart inverter has been utilized. The predefined intelligent Volt/VAr control characteristic (IVVCC) of an inverter has been considered in [22]. The inverter is supposed to follow the pre-specified IVVCC and inject or absorb reactive power based on local voltage signal. Thereafter, Volt/VAr control considering IEEE Std.1547-2018 has been proposed in [21]. Here also, a predefined IVVCC of the smart inverter and local voltage signal were utilized for reactive power injection or absorption. Furthermore, battery energy storage devices (BES) technologies are receiving increased attention. BES technologies are being accepted and deployed because of their salient benefits, such as real/reactive power support, load-demand balancing, and so forth. Effective use of BES under the energy internet has shown significant energy savings in a similar scenario [23], [24].

It has been observed that most existing literature does not comply with IEEE Std. 1547-2018, except [21]. A few works have considered reactive power support at constant power factor and full apparent power capability of the smart inverter. However, IEEE Std. 1547-2018 recommends a limited (44% of inverter's kVA rating) reactive power capability. Moreover, in available literature, a set of predefined operating points of IVVCC has been utilized while dealing with reactive support through smart inverters. Sometimes, the default operating points are incompatible with the local voltage signals, because the distribution grid may demand reactive power support through smart inverters in the dead-band range of IVVCC. That will not be possible due to the default operating settings. Therefore, an optimal IVVCC for each smart inverter is necessary to support the dynamic reactive demand.

The focus of the proposed study is to consider the participation of the DER in voltage and reactive power management. Thus, a VVO formulation has been developed in accordance with IEEE Std. 1547-2018. The scope of this paper is limited to reactive power capability and voltage/power control requirements. The important contributions of this paper are as follows:

TABLE I
SUMMARY OF EXISTING LITERATURE ON VOLT/VAR OPTIMIZATION WITH DISTRIBUTED GENERATION (DG)

Reference	Solution Technique	Volt/VAr control variables			Smart Inverter Consideration				
		OLTC/VR	CBs	Others	Inverter	Default IVVCC	Limited Q Capability	Optimal IVVCC	IEEE Std
[5]	HBMO	✓	✓	P of DG	×	×	×	×	×
[6], [7]	SFLA	✓	✓	P and Q of RES	×	×	×	×	×
[8]	TLA	✓	✓	P of RES	×	×	×	×	×
[9]	BSO	✓	✓	P of RES	×	×	×	×	×
[10]	GA	✓	✓	Q of SPV	×	×	×	×	×
[11]	GA	✓	✓	Q of WT	×	×	×	×	×
[12]	PSO and NN	✓	✓	Q of SPV	×	×	×	×	×
[13]	PSO	✓	✓	P and PF of DG	×	×	×	×	×
[14]	PSO	✓	✓	PF of WT	×	×	×	×	×
[15]	PSO	✓	✓	constant PF of DG	×	×	×	×	×
[16]	GA and PSO	✓	✓	constant PF of SPV and WT	×	×	×	×	×
[17]	CONOPT	✓	✓	unity PF of SPV	×	×	×	×	×
[18]	CPLEX	✓	✓	Q of SPV	✓	×	×	×	×
[19]	OPTI	✓	✓	P (curtailed), and Q of SPV	✓	×	×	×	1547-2003
[20]	GA	✓	✓	Q of SPV	✓	✓	×	×	1547-2014
[21]	CPLEX	✓	✓	Q of SPV	✓	✓	×	×	1547-2018
Proposed	GA and PS	✓	✓	Q and IVVCC of Inverters	✓	✓	✓	✓	1547-2018

1) Due to distinct voltage dependence of active-reactive powers of the loads and losses, the VVO of a future distribution system, in which minimization of apparent energy of the distribution system is considered instead of minimization of active energy. This VVO formulation has been ensured as per the DER interconnection guidelines of IEEE Std. 1547-2018.
2) In VVO formulation, the limited reactive power capability of a smart inverter has been taken into account while dealing with the reactive power dispatch. Thus, optimal dispatch of reactive power of inverters has been ensured in coordination with VVC devices.
3) Each smart inverter has been considered to operate on a different IVVCC. Therefore, determination of an optimal IVVCC has also been taken into account while achieving the VVO objectives. By deploying optimal IVVCC, maximum energy savings (in terms of both input energy and system losses) are obtained alongside minimal taps and switching operations of VVC devices.

The rest of paper is organized as follows: Section II explains the problem formulation by describing the models of loads, VVC devices, losses, and solar photovoltaic systems. In section III, a detailed description of various studied cases has been provided. The objective function, constraints, and solution technique of the proposed VVO formulation is covered in section IV. The results and discussion of the proposed algorithm on the test system are given in section V. The study is concluded in section VI.

II. Problem Formulation

A. Load Model

In a practical distribution system, the real and reactive components of a load shows different sensitivities to the terminal voltage. It has been observed that reactive power is more sensitive to voltage change [25]. The load to voltage dependency can be implemented using polynomial (ZIP) and exponential (EXP) load models. In this work, the EXP load model is utilized to represent the voltage dependence on real and reactive power of load. The EXP load models can be defined by,

$$P_{i,t}^{l}(V) = P_{i,t}^{\mathrm{r}} \left| \frac{V_{i,t}^{a}}{V_{i}^{\mathrm{r}}} \right|^{k_i^p} \tag{1}$$

$$Q_{i,t}^{l}(V) = Q_{i,t}^{\mathrm{r}} \left| \frac{V_{i,t}^{a}}{V_{i}^{\mathrm{r}}} \right|^{k_i^q} \tag{2}$$

where P^r, Q^r, and V^r are the rated real power, reactive power, and voltage of the load, respectively. Whereas, V^a represent the actual voltage. The voltage exponents of real (k^p) and reactive power (k^q) are different for practical loads [25].

B. Distribution Line Losses

The power from a substation to different loads will flow through distribution lines. Therefore, total complex power losses at a time t can be expressed as,

$$S_{\mathrm{loss},t}(V) = \sum_{i\in N_b} \sum_{j\in N_b} \left((r_{ij} + jx_{ij}) \frac{|V_{i,t}^{\mathrm{a}} - V_{j,t}^{\mathrm{a}}|^2}{2|z_{ij}|^2} \right) \tag{3}$$

The real and reactive power losses can also be evaluated by taking real (Re) and imaginary (*Imag*) part of (3), respectively. Here, N_b is a set of buses and z_{ij} is complex impedance of $i - j$ section.

C. Volt/VAr Control Devices

The traditional distribution network consists of OLTC, VR, and CBs as VVC devices. However, smart inverters would participate in Volt/VAr control and optimization. These inverters are capable of injecting or absorbing reactive power.

D. Solar Photovoltaic (SPV) System

Real power generated by a SPV system is a function of two factors, viz., solar irradiance (G) and cell temperature (T^c). These two parameters vary over a geographical area and time of the day. The output power of a SPV system (P^{pv}) can be defined by (4).

$$P_{n,t}^{\mathrm{pv}}(G, T^c) = P_n^{\mathrm{rated}} \frac{G_t}{G^{\mathrm{std}}} \left[1 + k_n^{\mathrm{Temp}}(T_{n,t}^c - T)\right] \tag{4}$$

where P^{rated} is the rated real power, G^{std} is the standard irradiance, k^{Temp} is the temperature coefficient, and T is the reference temperature. The output of SPV system is fed to the distribution grid through an inverter. Traditionally, an inverter is operated at a unity power factor (UPF). However, nowadays, smart inverters have been installed in distribution grids, which are capable of injecting/absorbing reactive power. The functionality of the smart inverter has been discussed in the next section.

III. The Proposed Study

The purpose of this study is to access energy savings in a distribution system with SPV system inverters in compliance with IEEE Std. 1547-2018. In this study, a total of five cases have been considered and their description is as follows:

A. Case-1: VVO Without SPV System

The Volt/VAr optimization is performed by the utility to schedule VVC devices in order to achieve the desired objective. In this case, the SPV systems are not considered in the distribution grid. Therefore, VVO is performed just by utilizing voltage regulators and switched capacitors connected at different locations in the network.

B. Case-2: VVO with SPV Inverters at Unity Power Factor

This case deals with the VVO performed in an active distribution grid where SPV systems are connected at various locations. These SPV units are interfaced with traditional inverters which are operating at UPF. Therefore, the inverters are considered to dispatch only real power to the network.

C. Case-3: VVO with Smart Inverters with Local Control

In this case, SPV systems with smart inverters are considered. These inverters operate based on local voltage measurements. In this case, utility performed VVO by coordinating VVC devices. At the same time, SPV systems are participating in reactive power dispatch using a predefined Volt/VAr curve.

Here, smart inverters can absorb or supply reactive power from/to the grid based on intelligent Volt/VAr control (IVVC) characteristics shown in Fig. 1. These IVVC characteristics (IVVCC) have to obey certain guidelines as specified in IEEE Std 1547-2018. The IVVCC is a piece-wise linear curve. Thus, it is combination of centralized (scheduling of VVC devices) and local (rule-based control of the smart inverter) control. The IVVC characteristics are described by (5).

$$Q_{n,t}^{\text{pv}}(V) = Q_n^{\max} \times \begin{cases} +1 & |V_{n,t}^a| < V_n^{O1} \\ +\frac{V_n^{O2}-|V_{n,t}^a|}{V_n^{O2}-V_n^{O1}} & V_n^{O1} \leq |V_{n,t}^a| < V_n^{O2} \\ 0 & V_n^{O2} \leq |V_{n,t}^a| \leq V_n^{O3} \\ -\frac{|V_{n,t}^a|-V_n^{O3}}{V_n^{O4}-V_n^{O3}} & V_n^{O3} < |V_{n,t}^a| \leq V_n^{O4} \\ -1 & |V_{n,t}^a| > V_n^{O4} \end{cases} \tag{5}$$

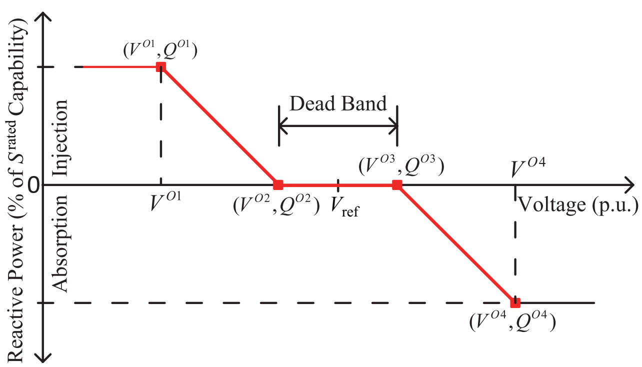

Fig. 1. Intelligent Volt/VAr control (IVVC) characteristics of smart inverters.

The operating points of IVVCC, as per IEEE Std. 1547-2018, are given in Table II. The actual reactive power dispatch of a smart inverter depends on these operating points (where $V_{\text{ref}} = 1$) and reactive power capability ($Q^{\max} = 0.44S_n^{\text{rated}}$). In this case, the default IVVCC will remain the same for each smart inverter.

TABLE II
OPERATING POINTS OF IVVCC FOR LOCAL CONTROL

V^{O1}	V^{O2}	V^{O3}	V^{O4}	Q^{O1}	Q^{O2}	Q^{O3}	Q^{O4}
0.92	0.98	1.02	1.08	$+Q^{\max}$	0	0	$-Q^{\max}$

D. Case-4: VVO with Smart Inverters with Optimal IVVCC

In the previous case, default set points of IVVCC are used (see Table II) that can be utilized for the local control purposes. However, the IVVCC (5) indicates the extent of reactive power injection or absorption depends on the set points (V_n^{O1}, V_n^{O2}, V_n^{O3}, and V_n^{O4}) of the characteristics. These set points have certain limits (specified in IEEE Std 1547-2018) and described by (6), (7), (8), and (9).

$$0.82 \leq V_n^{O1} \leq 0.95 \tag{6}$$

$$0.97 \leq V_n^{O2} \leq 1.00 \tag{7}$$

$$1.00 \leq V_n^{O3} \leq 1.03 \tag{8}$$

$$1.02 \leq V_n^{O4} \leq 1.18 \tag{9}$$

$$V_n^{O2} \leq V_n^{O3} < V_n^{O4} \tag{10}$$

Variations of these settings impact reactive power generation and absorption by the inverters. Therefore, the SPV systems can be effectively utilized for reactive power injection or absorption. Distribution system operators (DSOs) can schedule the VVC devices along with optimal voltage settings of the smart inverters with the information of operating parameters (such as voltage, current, taps of regulators, switch positions of capacitors). In this case, the DSOs are responsible for coordinated optimal IVVCC settings and VVC devices in order to achieve maximum energy savings. The operational and system constraints also include boundary constraints of the voltage set points for IVVCC of smart inverters installed in the distribution network. For stable operation of inverters an additional inequality constraint has also been defined in (10). Thus, there are a few additional control variables (V_n^{O1}, V_n^{O2}, V_n^{O3}, and V_n^{O4}) alongside voltage regulators and capacitors settings.

E. Case-5: VVO with Smart Inverters Considering Reactive Capability Curve

In this case, inverters of SPV systems are considered to be capable of injecting (+) and absorbing (−) reactive power for real power output levels as per capability characteristics shown in Fig. 2. It can be mathematically described by (11).

$$Q_{n,t}^{\text{pv}}(P) = \begin{cases} \pm\frac{Q_n^{\max} \times P_{n,t}^{\text{pv}}}{0.20 \times P_n^{\text{rated}}} & 0.05P_n^{\text{rated}} \leq P_{n,t}^{\text{pv}} \leq 0.2P_n^{\text{rated}} \\ \pm Q_n^{\max} & P_{n,t}^{\text{pv}} > 0.2P_n^{\text{rated}} \end{cases} \tag{11}$$

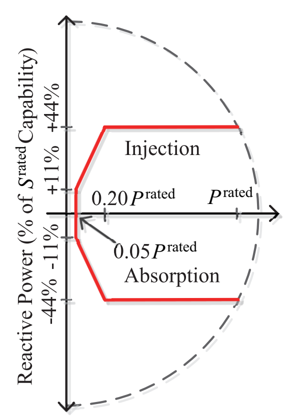

Fig. 2. Reactive power capability characteristics for smart inverter.

Therefore, in this case, the reactive power of inverters is considered as a control variable and supposed to be scheduled by the utility within the boundary conditions as defined in (11). Here, the optimal dispatch of reactive power of inverters has been ensured in coordination with VVC devices. Therefore, the purpose of this case is to optimally schedule the VVC devices and reactive power of PV inverters in order to obtain the maximum energy savings.

IV. PROPOSED ALGORITHM

A. Objective Function

The active and reactive power components of a practical load show distinct characteristics with variation in the terminal voltage. The voltage sensitivities of each class of customer are different [25]. Therefore, Volt/VAr control in a distribution network influences both active and reactive load demands.

The objective of this paper is the minimization of apparent energy demand of the distribution network. Minimization of apparent energy demand leads to minimization of both real as well as reactive components. The objective function can be mathematically defined by (12).

$$\min f = SSE_{\text{apparent}} = \sum_{t=1}^{24} |SS_{\text{demand},t}| \tag{12}$$

where

$$SS_{\text{demand},t} = \sum_{i\in N_b} \left(P_{i,t}^l + jQ_{i,t}^l\right) + (S_{\text{loss},t}) - \sum_{n\in N_{\text{pv}}} \left(P_{n,t}^{\text{pv}} + jQ_{n,t}^{\text{pv}}\right) - \sum_{k\in N_{cb}} jQ_{k,t}^{\text{cap}} \tag{13}$$

The first part ($\sum_{i\in N_b}\left[P_{i,t}^l + jQ_{i,t}^l\right]$) represents the apparent load of different customers in the network, the second part is the apparent power loss ($S_{\text{loss},t}$), the third part ($\sum_{m\in N_{\text{pv}}}\left[P_{m,t}^{\text{pv}} + jQ_{m,t}^{\text{pv}}\right]$) is the apparent power generated by solar photovoltaic generators of the network, and $\sum_{k\in N_{cb}} Q_{k,t}^{\text{cap}}$ is the kVAr supplied by capacitor units. Therefore, the objective is to get the optimal schedule of VVC devices alongside IVVCC of smart inverters such that the daily apparent energy demand of the distribution network can be minimized.

B. System and Operational Constraints

In addition to the constraints defined in (5)–(11), the other operational and system constraints are defined by (14)–(20).

1) System Voltages at Buses

The voltage variation at each bus is constrained between $V^{\min}$ and $V^{\max}$. It can be represented by (14).

$$V_i^{\min} \leq |V_{i,t}^a| \leq V_i^{\max} \tag{14}$$

2) Tap Settings of Voltage Regulators

The regulation ratio for a voltage regulator can be represented by (15).

$$V_{j,t}^{\text{VR}} = 1 + \Delta V_j \times TAP_{j,t}^{\text{VR}} \tag{15}$$

where $TAP_{j,t}^{\text{VR}} \in \{-16,\cdots,-1,0,+1,\cdots,+16\}$. Daily tap operations are fixed in order to avoid wear-n-tear cost of a tap changing mechanisms. This limit can be mathematically expressed by (16).

$$\sum_{t=2}^{24} |TAP_{j,t}^{\text{VR}} - TAP_{j,t-1}^{\text{VR}}| \leq DATO_j(=60) \tag{16}$$

where $DATO_j$ is the daily allowable tap changing operations of j^{th} voltage regulator.

3) Capacitor Banks

The reactive power supplied by k^{th} switched capacitor at time t can be represented by (17).

$$Q_{k,t}^{\text{cap}} = SW_{k,t}^{\text{cap}} q_k^{\text{cap}} \left|\frac{V_{k,t}^a}{V_k^{\text{r}}}\right|^2 \tag{17}$$

where switch status ($SW_{k,t}^{\text{cap}}$) can be either '*on*' ('1') or '*off*' ('0'). The limitation on daily allowable switching operation (DASO) is necessary to avoid frequent replacement of devices and this can be defined by (18).

$$\sum_{t=2}^{24} |SW_{k,t}^{\text{cap}} - SW_{k,t-1}^{\text{cap}}| \leq DASO_k(=6) \tag{18}$$

4) Reactive Power Compensation Limit

The reactive power provided by capacitor units and smart inverters does not exceed the required reactive demand of the network any point of time. These constraints can be defined by (19).

$$\left(\sum_{k\in N_{cb}} Q_{k,t}^{\text{cap}} + \sum_{n\in N_{\text{pv}}} Q_{n,t}^{\text{pv}}\right) \leq \left(\sum_{i\in N_b} Q_{i,t}^l + Imag(S_{\text{loss},t})\right) \tag{19}$$

5) Line Loading Limit

The loading ($\sqrt{P_{ij,t}^2 + Q_{ij,t}^2}$) of a line or cable has to be less than or equal to its maximum loading ($S_{ij}^{\max}$). This can be mathematically shown by (20).

$$\left(\sqrt{P_{ij,t}^2 + Q_{ij,t}^2}\right) \leq S_{ij}^{\max} \tag{20}$$

C. Solution Technique

The objective function (12) and constraints (5–11, 14–20) are nonlinear with discrete, as well as continuous variables. The control variables are taps of voltage regulators (integers), switch positions of capacitors (binary), operating points of IVVCC (continuous) and kVAr output of SPV system (continuous). Therefore, heuristic techniques are more suitable to deal with such a problem. Many works of literature on VVO have utilized heuristic methods (see Table I). Moreover, it can be seen that particle swarm optimization (PSO) and genetic algorithm (GA) have been broadly acknowledged to tackle VVO problems. While solving the VVO problem, it has also been observed that PSO converges faster than GA, but (sometimes) it converges to a sub-optimal solution [16]. Therefore, in this research GA has been used as an optimization technique. In order to make it fast, the initial solution has been obtained with GA and then the pattern search (PS) algorithm has been utilized for obtaining the global solution.

V. Results and Discussion

In this study, the modified IEEE-123 node test distribution system [26] is considered. The topology of the modified IEEE-123 node feeder is shown in Fig. 3. The connected loads in the system are assumed to be voltage-dependent, which are of constant power, constant current, and constant impedance type. In urban areas, a practical distribution system may have (some feeders dedicated for) industrial loads (like factories), commercial establishments (such as schools, offices, restaurants, and so on), and residential units (apartments, hostels, individual homes, etc.). Therefore, in this study, the total load $(3.49 + j1.92)$ MVA of the distribution network is shared by industrial, commercial, and residential loads. The percentages of load shared by industrial, commercial, and residential customers are 44.72, 20.77, and 34.51%, respectively. The hourly load variation of these customers is adopted from [27]. This modified system also consists of SPV systems connected at nodes 95, 115, 117, and 122 in the network of 275 kVA each. Three capacitors at nodes 88a, 90b, and 92c of 100 kVAr and one capacitor at node 83 of 600 kVAr are also there in the system. The required solar irradiance and temperature data are displayed in Fig. 4. The modified data of the IEEE-123 bus system utilized in this study is accessible online at [28]. In this study, Matlab COM interfacing of OpenDSS [29] has been utilized for time-series load flow calculations and genetic algorithm inspired pattern search has been utilized for optimal settings of control variables. Simulations are carried out on modified IEEE-123 node feeder for the various cases discussed in Section III.

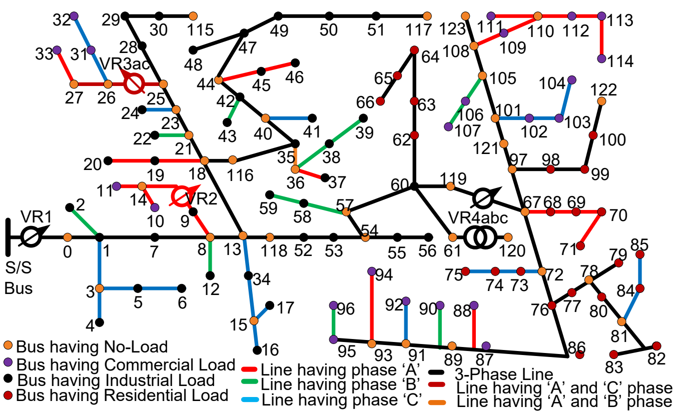

Fig. 3. Modified IEEE-123 bus radial distribution test system.

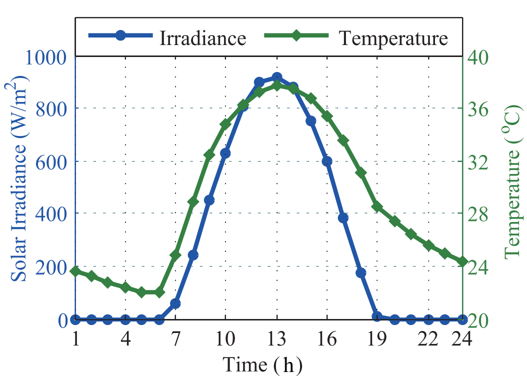

Fig. 4. Input parameters for solar photovoltaic generators.

All computations have been performed on Intel Core i7-8700 8th generation processor CPU @ 4.6 GHz, multi-core (6 cores), 16 GB RAM system. Optimization is performed utilizing the Parallel Computing Toolbox of MATLAB, where all 6 cores of the system have been used. The CPU time and convergence characteristics are the important factors to demonstrate the robustness of an algorithm. The convergence characteristics of the studied cases are displayed in Fig. 5. The computational time (in seconds) for Case-1, Case-2, Case-3, Case-4, and Case-5 is 9.7592×10^3, 9.8787×10^3, 10.7978×10^3, 16.1348×10^3, 11.6907×10^3, respectively. The performance of these cases is discussed in the following subsections.

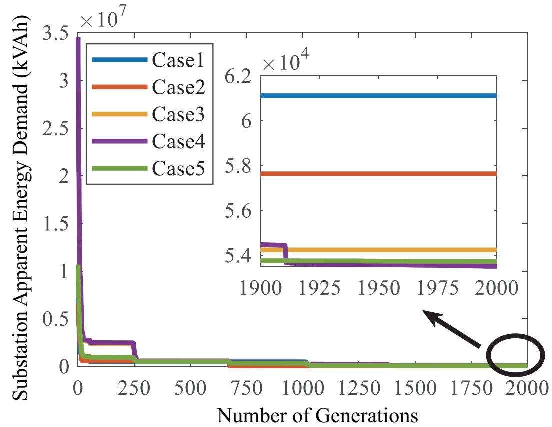

Fig. 5. The convergence characteristics of all the studied cases.

A. Substation Energy Savings

Energy savings obtained for different cases are listed in Table III. In Case-2, the MVArh demand has been reduced by 5.98% where inverters are operating at UPF. Overall savings increased when the operation of smart inverters is taken into account. Savings in Case-4 are the highest among all the cases. It is also observed that utilizing a predefined IVVCC is a less efficient practice for the purpose of utility energy savings. More savings can be attained by selecting an optimal IVVCC for each smart inverter. Thus, up to 51.56% MVArh savings have been obtained with the optimal IVVCC. However, utilizing inverters with limited reactive capability (Case-5) is found to be the second most efficient method. Here, the highest reduction in energy losses (upto 16.03%) is achieved.

TABLE III
SUBSTATION ENERGY INPUT AND LINE LOSSES

Description		Case-1	Case-2	Case-3	Case-4	Case-5
Substation Energy	MVAh	61.11	57.63	54.24	53.51	53.73
	MWh	59.75	56.35	53.18	53.15	53.16
	MVArh	12.83	12.06	10.65	6.22	7.78
	ΔMVAh	–	5.70%	11.24%	12.44%	12.34%
	ΔMWh	–	5.69%	11.00%	11.05%	11.04%
	ΔMVArh	–	5.98%	17.04%	51.56%	39.34%
Line Energy Loss	MVAh	2.43	2.20	2.06	2.09	2.03
	MWh	1.09	0.99	0.93	0.94	0.91
	MVArh	2.17	1.97	1.84	1.86	1.81
	ΔMVAh	–	9.22%	15.30%	14.05%	16.31%
	ΔMWh	–	9.00%	14.96%	13.82%	16.03%
	ΔMVArh	–	9.27%	15.39%	14.10%	16.38%

The hourly MVAr demand of the distribution system, and corresponding supply by the utility and local generators are displayed in Fig. 6. In the first two cases (Case-1 and Case-2), the reactive power supplied by the utility is more, since

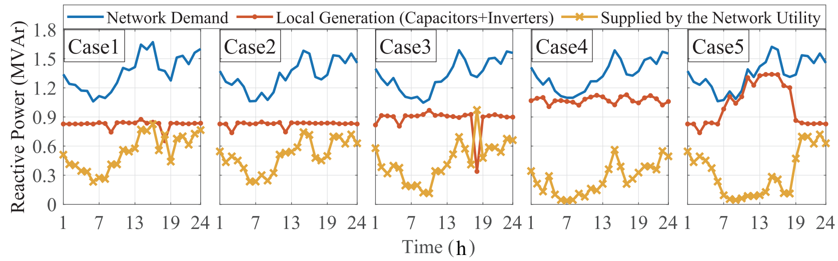

Fig. 6. Hourly demand (load plus losses) and supply (local generation plus utility) of reactive power in various cases.

a limited MVArs locally are supplied from capacitor banks. However, in other cases, the reactive power supplied by SPV systems and capacitors has been utilized to minimize the dependency on the grid. It can also be observed that reactive support received from the SPV systems is subsequent when considering smart inverters. In Case-4, the local availability of reactive power is varying from 1.0 to 1.2 MVAr (i.e., the highest energy supply from local generators). This variation is fluctuating greatly in Case-5 because in the day time, both inverters (under limited capability) and capacitors are supplying MVArs. However, during night, only capacitors are supplying MVArs because the reactive power output of a smart inverter is a function of real power generation.

The hourly reductions in the utility's active and reactive demand can be seen in Fig. 7. Active demand increases (shown with negative bar) during a period when smart inverters are not producing real power (Fig. 7(a)), whereas a significant reduction (5%–35%) has been recorded in the day time (7th to 18th hour). The reduction pattern is almost similar for Case-3 to Case-5. Moreover, reactive demand is greatly affected and its percentage reduction is displayed in Fig. 7(b). Reactive demand also increased at some hours (mostly when no sun shines). In Case-3, the reactive power of the smart inverter depends on predefined IVVC characteristics. In this case, at some hours (1st, 4th, 5th, 18th, and 19th hours), the total available reactive power (from smart inverters and capacitors) is less than in Case-1. For these hours, more reactive power must be drawn from the substation (in order to meet the demand). In Case-4, smart inverters are dispatching reactive power based on optimal IVVC characteristics. Overall reactive power drawn from the substation is substantially reduced at every hour of the day because of sufficient dispatch of kVAr through smart inverters and capacitors. In Case-5, dispatch of reactive power is a function of active power. Thus, there will not be kVAr dispatch by smart inverters from 7 pm to 6 am. Therefore, local kVAr dispatch is only possible through capacitors. Henceforth, during these hours, the DSO has to draw more reactive power from the grid as compared to Case-1. Moreover, from the 8th to 18th hours, smart inverters can dispatch maximum reactive power compared to other cases. But it can also be noted there will be no increase in reactive demand if all smart inverters are operating on the optimal IVVCCs (Case-4). Reactive demand reduction is highest at a few hours when limited reactive capability of smart inverters has been taken into account (i.e., Case-5). Overall, positive demand reductions (varying from 15%–85%) have been obtained in Case-4.

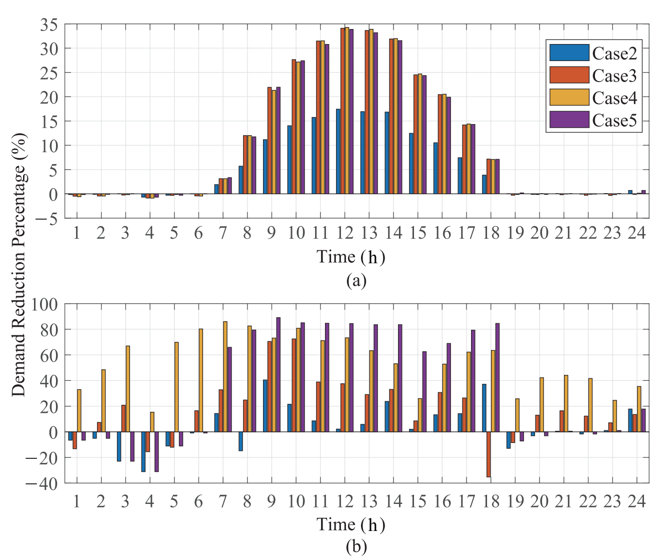

Fig. 7. Hourly demand reductions of the utility responsible for power supply (a) real power, (b) reactive power.

B. Optimal Dispatch Schedule of VVC Devices and kVAr of Smart Inverters

The optimal dispatch of various VVC devices and reactive power of SPV systems have been ensured to achieve maximum energy savings. The hourly schedule of different regulators corresponding to the studied cases has been shown in Fig. 8. It can be observed that tap schedule of each regulator is unique and gets affected with the studied cases. The daily tap operations of each regulator are less than allowable operations and shown in Table IV.

TABLE IV
DAILY TAP OPERATIONS OF VVC DEVICES

VVC Device		Case1	Case2	Case3	Case4	Case5
Regulators	VR1	42	37	31	25	36
	VR2 (a-ϕ)	29	33	32	22	40
	VR3 (a-ϕ)	44	33	30	25	48
	VR3 (c-ϕ)	34	37	29	29	41
	VR4 (a-ϕ)	45	34	34	28	40
	VR4 (b-ϕ)	7	14	19	15	46
	VR4 (c-ϕ)	28	28	42	27	60
Capacitors	Cap83	0	0	2	0	0
	Cap88a	0	2	0	0	6
	Cap90b	4	2	1	0	6
	Cap92c	2	0	2	0	2

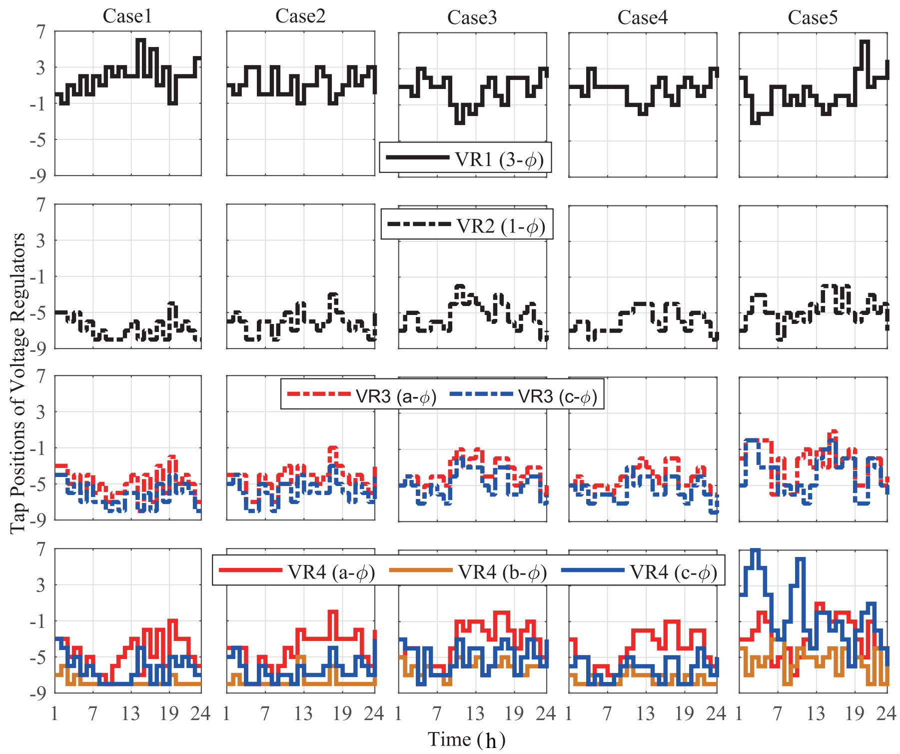

Fig. 8. The optimal schedule of tap positions of voltage regulators in various cases.

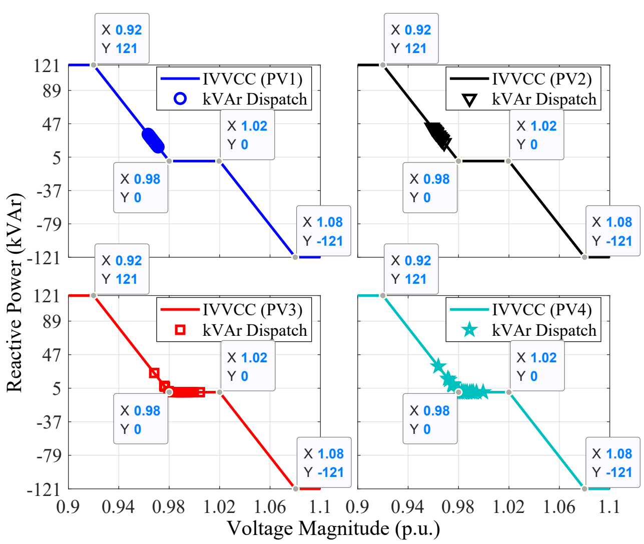

Fig. 9. The reactive power dispatch followed by a predefined IVVCC of smart inverters.

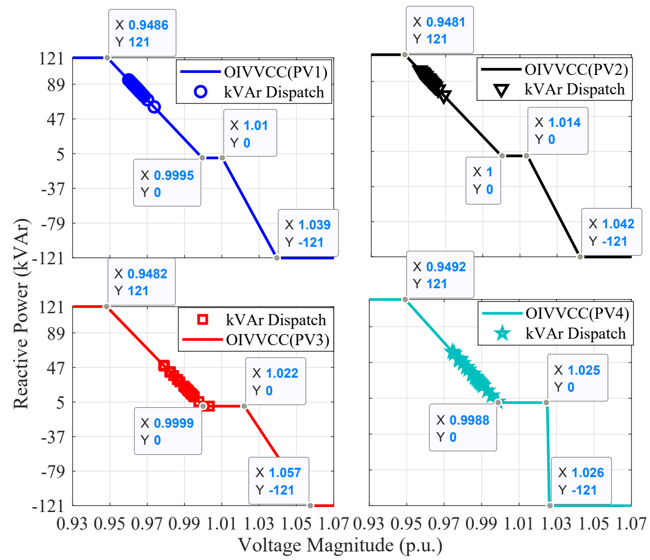

Fig. 10. The reactive power dispatch followed by optimal IVVCC (OIVVCC) of smart inverters.

The kVAr output of smart inverters utilizing a predefined IVVCC (Table II) can be in Fig. 9. Here, the reactive power output of the first two SPV systems (i.e., PV1 and PV2) is varying from 18 to 43 kVAr, whereas, the kVArh supplied by the second one is more (PV1: 643 kVArh and PV2: 811 kVArh). Remaining SPV systems are producing only a few units of reactive energy (PV3: 42 kVArh and PV4: 114 kVArh) in a day. This is due to the fixed operating points of the IVVCC, where kVAr dispatch is not allowed in the dead-band (0.98 to 1.02) of the characteristic even if it is demanded by the network. To overcome this issue, the concept of optimal IVVCC (OIVVCC) has been considered in Case-4. The OIVVCC (operating points shown with data cursor) alongside kVAr dispatched by inverters is shown in Fig. 10. Here, the operating points of IVVCC have been determined in coordination with the optimal dispatch schedule of VVC devices. The obtained OIVVCC of each inverter is unique and compatible with network conditions. Therefore, the kVAr dispatched by smart inverters increased. In this case also, the reactive energy produced by PV1 system is more than three times when compared to the previous case, i.e., 2000 kVArh.

The other SPV systems have also supplied a major part of reactive energy demanded by the network (PV2: 2198 kVArh, PV3: 597 kVArh, and PV4: 807 kVArh).

In Case-5, the optimal dispatch of kVAr of smart inverters is based on the feedback signal received from the power utility. The optimal kVAr dispatch with respect to real power output of inverter is shown in Fig. 11. In this case, all SPV systems (except PV1) are supplying (injecting) reactive power to the distribution grid up to the allowable capability of the inverter. Reactive power is not produced when there is no real power production (means no sunshine). There are some hours when PV1 is absorbing reactive power from the grid. Daily kVArh supplied by PV1, PV2, PV3, and PV4 is 446, 1324, 1358, and 1357, respectively.

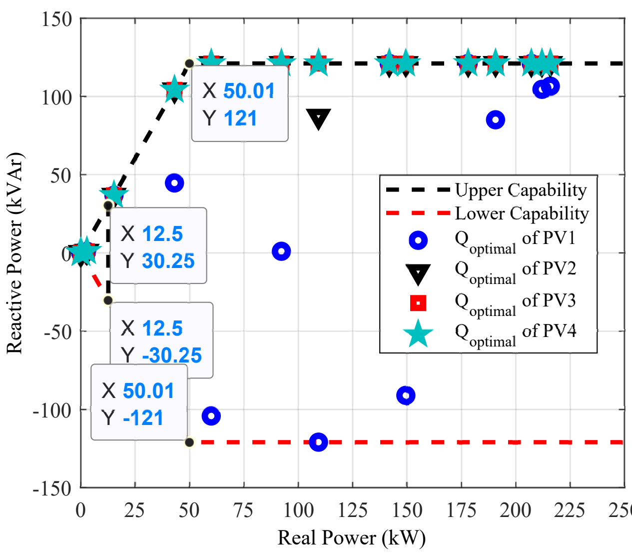

Fig. 11. The optimal reactive power dispatch considering limited reactive power capability of smart inverters.

C. Final Remarks

The obtained real energy savings are 5.69% just by allowing penetration of SPV systems in the grid (Case-2). Further, an improvement up to 5% (approx) has been seen when SPV systems paired with smart inverters utilizing predefined IVVCCs (local control) have been allowed (Case-3). Moreover, smart inverters lead to a huge reduction in the reactive power demand of the substation (Fig. 12). Consequently, a reduction of upto 51.56% in reactive energy (kVArh) supplied from the utility has been seen. It can also be noticed that maximum energy savings (MVAh, MWh, and MVArh) can be obtained if smart inverters are allowed to operate on optimal intelligent Volt/VAr characteristics (Case-4). Significant reduction in energy losses can also be seen in the studied cases. Maximum loss reduction (upto 16.03%) has been obtained when centralized dispatch of reactive power of inverters is considered alongside VVO.

Daily taps and switching operations of VVC devices are affected when scheduling them for energy savings in presence of SPV systems. In order to avoid frequent maintenance and replacement of these devices, limited VVC operation are needed. It is also observed that both demand (MVAh) and operation (of VVC devices) are minimal for the case when optimal intelligent Volt/VAr control characteristics have been taken into the account (Case-4). However, from the view point of MVAh demand, optimal dispatch of reactive power utilizing limited reactive capability can be considered as a second choice but with increased (or maximum) operations of VVC devices.

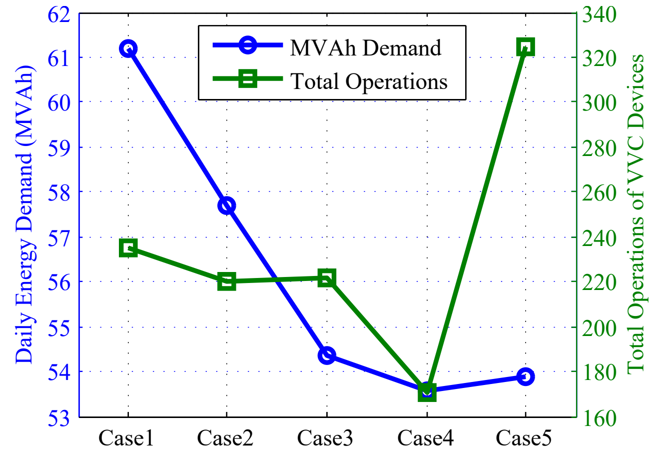

Fig. 12. The apparent energy demand of the utility versus total operation of VVC devices of the network.

VI. Conclusion and Future Research Scope

In this paper, the maximization of energy saving of a distribution network has been ensured considering intelligent Volt/VAr control based on recent IEEE Std. 1547-2018. Inverters based on local settings of intelligent Volt/VAr control are not effective in terms of reactive power utilization within the inverter capability. Thus, strategy based on optimal IVVCC has been proposed to mitigate this issue. The performance of optimal IVVCC has been validated with a set of predefined operating points of the same characteristics (adapted from IEEE Std. 1547-2018) and limited reactive capability of smart inverters. Maximum savings have been obtained when smart inverters are controlled by utilizing the optimal IVVCC in coordination with VVC devices. The optimal IVVCC not only minimizes the input energy, but also energy loss in the grid. Moreover, it ensures minimal taps and switching operations of VVC devices.

Furthermore, it has been observed that reactive demand is increasing at some hours of the day. This problem can be mitigated by considering time-based scheduling of various strategies of smart inverters. Thus, the time-based scheduling of different smart inverter functions (alongside VVO objectives) can be considered as a future scope. It is also noticed that VVC devices have many switching and tap operations which leads to frequent maintenance (this involves a cost). Thus, in the future, the energy-savings estimation can be performed by considering the minimization of the cost of taps and switching operation of VVC devices alongside other VVO objectives.

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