Determining the Optimal Setting of Voltage Regulators for Day-Ahead Management of Distribution Smart Systems

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***Abstract*—Environmental pollution and greenhouse gas emissions, as well as oil depletion are prime motivators for the development and adoption of renewable power sources. However, the traditional operating philosophy of power systems and the random nature of these sources represent an important barrier for their massive deployment. Fluctuations of wind and solar power generation integrated as distributed sources can induce important variations on the voltage profile, leading to values out of the range typically suggested by power quality standards. To deal with this problem, in this paper the optimal setting of voltage regulators (VRs) at each hour has been optimally determined by implementing a genetic algorithm with integer codification, so that it can be effectively integrated with the load flow methodologies currently available in the literature without requiring any linearization process. Results obtained from the analysis of a case study reveal the behavior of the optimal VR settings and reactive power compensation on a daily basis, which are highly correlated with the daily load profile.**

***Index Terms*—Distributed generation; Distribution system; Genetic algorithm; Voltage regulator; Smart grid.**

I. INTRODUCTION

Massive and fast technological development experienced by many countries worldwide has increased the environmental pollution levels and global warming until worrying values, taking all the attention to the development of renewable energy sources or clean energies. However, the traditional rules of distribution systems and their operating philosophy make the integration of renewable energies a difficult task due to the increment on system variability and uncertainty, voltage variations, bidirectional power flows, as well as the increment on the fault levels and the degradation of the setting of some protective devices [1]. Operating constraints and behavior of the voltage profile in distribution smart systems provided with distributed generation (DG) has been widely analyzed in the literature; in general sense, the effects integrating DG depends on the customer demand, penetration level, voltage level of distribution feeder, among other factors. Traditionally, behavior of voltage profile has been managed by means of an on load tap changer (OLTC), switched capacitors, and step voltage regulators (VRs).

Moreover, other methods related to the generation curtailment during hours of low demand, incorporation of reactive power control devices, coordinated operation of OLTC, control of the inverters installed with DG, implementation of demand response programs, and installation of energy storage systems have been recently suggested [2]. In the technical literature, many strategies to the optimal control of voltage profiles in order to increase and improve the accommodation of renewable generation have been proposed. In [3], a fuzzy control system for voltage control at substation level was developed. It takes the advantage of fuzzy systems to work with approximate and qualitative information in order to maintain system voltage within an accepted interval. In [4], a methodology based on managing local controllers installed around the distribution system in order to remove a voltage-related operational violation was proposed. The methodology uses the communication between local controllers to determine the appropriate reactive power injection to improve the system voltage. In [5], a cooperative control strategy for voltage control considering unbalanced loads was proposed; the method adjusts transformers tap-changer and DG settings in order to minimize the voltage deviations and reducing the tap operation; this is carried out by performing an optimization analysis with these two conflicting objectives.

In [6], a methodology based on a decentralized control of active and reactive power with a sensitivity analysis was proposed to maintain system voltage within the required limits, while power losses and reactive power delivered by DGs are minimized. In [7], an online operating strategy was proposed to deal with the problem of several DGs working simultaneously to eliminate a determined voltage violation; the presented methodology minimizes the degree of conflicts between devices by prioritizing the operation of each VR. In [8], coordinated operation of photovoltaic (PV) generation and a battery energy storage system (BESS) to provide voltage control in rural and urban systems was proposed; according to the observed results, voltage variations on urban systems could be managed by using reactive power compensation from PV generation.

However, in [8], in the case of rural systems, the coordinated operation of PV and BESS is suggested. In [9], distributed PV generators and tap-changers are controlled by using information related to the tap-changer settings, which is obtained by performing a day-ahead analysis using predictions of load demand and PV power generation; from this analysis, reference settings are obtained and included on a re-planning algorithm in order to minimize the effects of forecasting error. In [10], several strategies for self-consumption and voltage control at local level in residential systems were developed and evaluated; such strategies were designed as a combination of a special BESS charging, reactive power injection, and curtailment of PV power generation.

In [11], a control strategy at which BESS is charged during the peak generation of PV system and discharged during peak-load hours was proposed. This strategy is to be implemented on a control system with distributed and localized capacities; distributed control is based on consensus algorithm in order to regulate the system voltage, while the localized control manages the state of charge of BESS. In [12], a control algorithm to manage OLTC using state estimation and reactive power compensation on the local wind generator was proposed and tested.

In this paper, coordinated day-ahead operation of VRs and static reactive power compensators (SRPCs) are analyzed by means of a genetic algorithm (GA) formulated to improve the voltage profile. In this way, the position of each VR, as well as, the amount of reactive power to be injected by SRPC installed with DG can be optimally determined. The rest of the paper is organized as follow: section II explains the proposed methodology, section III describes the capabilities of the proposed method through the analysis of a case study; and then, main conclusions are discussed in section IV.

II. PROPOSED METHOD

As stated before, in this work is presented a control method to be implemented on energy distribution systems provided with renewable DG in order to enhance its voltage profile by manipulating the settings of VRs in an optimal way, taking into account the effects of other reactive power controls devices such as SRPCs. The proposed methodology requires a day-ahead forecasting of load demand [13] at each distribution transformer; as well as, a power forecast of each renewable DG unit installed on the system [14]. Historical information could be obtained from the system by using the communication infrastructure of smart grid [15], which is needed by many forecasting tools currently used. Setting of each VR typically consists of 32 steps to increase or reduce the voltage to be controlled [16]. Considering this setting as a discrete value, it could be incorporated into an optimization problem as a discrete variable.

In this work, optimization of voltage profile has been chosen as the main objective to be enhanced, representing the settings of each VR as an integer variable. In order to consider the influence of reactive power flow on the voltage profile, a GA has been implemented, so that an iterative load flow solution [17] can be effectively applied without any linearization process, which is frequently used in the application of mixed-integer linear programming approach.

Regarding the influence of SRPCs, these has been considered by using the model proposed in [18], where the amount of reactive power required to get a determined voltage value (typically, the nominal voltage of distribution system) is estimated and then added to the load flow analysis.

Let n $(n = 1, \ldots, N)$ be the index to represent each node of distribution system, and m those branches of distribution system with VR represented by the set $m \in \{a, b, c, d, e\}$, where are a, b, c, d, e are specific branches of the system. Let i $(i = 1, \ldots, I)$ be the index of each individual of GA represented by the structure $VR_m^i \in \{|VR_a^i| \ldots |VR_e^i|\}$, and g $(g = 1, \ldots, G)$ the index for each generation of GA. The optimization algorithm could be implemented by following these steps [19]:

- Step 1: Set the number of generations (G), population size (I), crossover rate (R), and mutation rate (W).
- Step 2: Set the generation under analysis to 1 by assigning $g \leftarrow 1$.
- Step 3: Using a generator of random numbers, the initial population of GA is created, taking into account the limits of the tap position to reduce voltage profile (VR_{min}) or to increase it (VR_{max}).
- Step 4: For each individual of the population (i), objective function (O_i) is estimated by using (1),

$$O_i = \sum_{n=1}^{N} |V_n - \bar{V}|\,; i = 1, \ldots, I \qquad (1)$$

where $\bar{V}$ is the nominal voltage of the system. Each voltage is determined by solving load flow problem with the corresponding tap positions $(\mathrm{VR}_\mathrm{m}^\mathrm{i})$.

- Step 5: Fitness of each individual $(\mathrm{f_i})$ is estimated by using (2), defined according to the magnitude and order of $\mathrm{O_i}$,

$$f_i = \{(I + 1) - i\} \Big/ \sum_{j=1}^{I} \{(I + 1) - j\}\,; i = 1, \ldots, I. \qquad (2)$$

- Step 6: Apply reproduction, crossing, and mutation operators following the values specified at Step 1.
- Step 7: If $(\mathrm{g} < \mathrm{G})$; then assign $\mathrm{g} \leftarrow \mathrm{g} + 1$ and go to Step 4; else stop.

III. CASE STUDY

The performance of the proposed methodology is illustrated through the analysis of the system shown in Figure 1, modified from [20]. This system has three VRs installed in branches 4, 5 and 8 and a wind farm on node 12 provided with a SRPC to maintain the voltage at its nominal value ($\bar{\mathrm{V}}$=13.8 kV).

Resistance and reactance per branch; as well as, the rated capacity of each distribution transformer installed at the receiving node are presented in Table I; while Figures 2 and 3 show day-ahead load-demand and wind power forecasting. As stated before, GA has been implemented by considering VR settings as integer numbers between (VR_{min}= -5 and VR_{max}= +5) with objective function defined in (1).

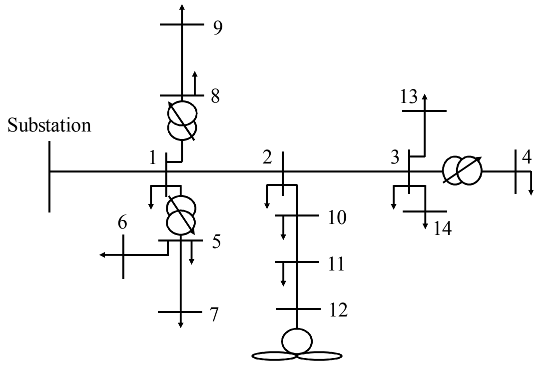

Figure 1. Distribution system under analysis.

TABLE I - DISTRIBUTION SYSTEM DATA

Sending node	Receiving node	Resistance (Ω)	Reactance (Ω)	Power (kVA)
Substation	1	1.35309	0.32349	63
1	2	1.17024	1.14464	100
2	3	0.84111	0.82271	200
3	4	1.52348	1.0276	50
1	5	2.55727	1.7249	200
5	6	1.0882	0.734	200
5	7	1.25143	0.8441	200
1	8	2.01317	1.3579	100
8	9	1.68671	1.1377	100
2	10	1.79553	1.2111	200
10	11	2.44845	1.6515	100
11	12	2.01317	1.3579	---
3	13	2.23081	1.5047	100
3	14	1.19702	0.8074	200

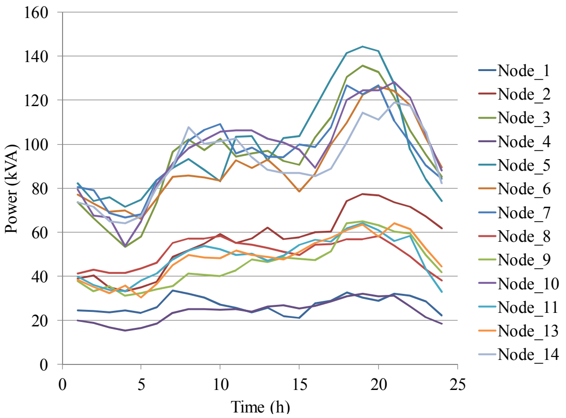

Figure 2. Load demand forecasting per node.

This optimization approach has been solved during each step of the horizon of schedule (24 h) using the parameters shown in Table II. Figure 4 shows the position of each VR; it should be highlighted that, VR-position should be changed to compensate the hourly variations of the load profile; as VR installed in branch 5 manages a higher load than those installed at branches 4 and 8, its position remains higher between 7h and 23h.

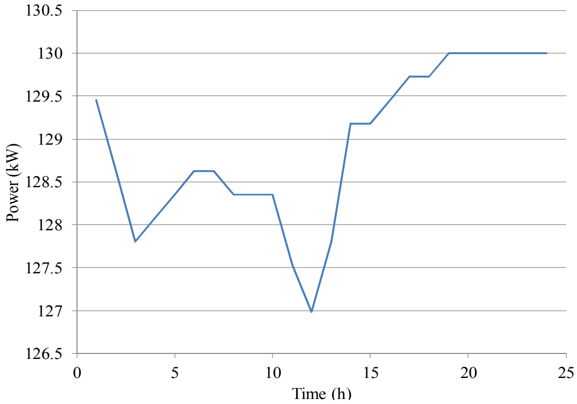

Figure 3. Wind power forecasting at node 12.

TABLE II - GA PARAMETERS

G	I	R (%)	W (%)
25	300	90	1

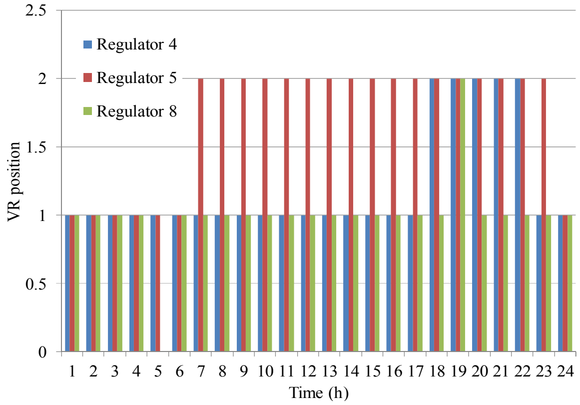

Figure 4. Position of each VR.

Figure 5 shows the hourly profile of the reactive power to be injected into the system by SRPC installed in the node 12 with the wind farm to maintain the voltage at 13.8 kV. According to these results, it is clear how the hourly profile of aggregated load-demand directly influences the reactive power required to the voltage compensation.

Figures 6, 7 8 show the voltage profile during 1h-8h, 9h-16h, and 17h-24h time intervals, respectively. The work centers its analysis on the nodes 4-7, and 9 because these are extreme points on the system affected by the operation of VRs. Regarding the voltage of node 4, during the morning (Figure 6) the voltage is around the nominal value with a lightly lower value at 7h and 8h because the increment of load demand starts around these hours.

During morning/afternoon (Figure 7) voltage decreases to a value between 13.75kV (99.63%) and 13.8kV because the load demand increases, while VR-position remains constant. During afternoon/night (Figure 8) peak-load is reached and VR-position changes to compensate the operational conditions; as a consequence, voltage increases to a value between 13.8kV and 13.85kV (100.36%); however, during 23h and 24h, VR-position changes and consequently voltage at node 4 reduces to a value between 13.75kV and 13.8kV.

With respect to the voltage of node 9; as VR-position remains constant during almost all day, this node is influenced by the variations of load-demand profile; however, as VR-position is changed at 19h, voltages of nodes 8 and 9 increases to 13.85kV.

In respect of the voltages of nodes 5, 6, and 7, these are influenced by the VR installed on branch 5, which works at a high position during the afternoon; then, voltages at these nodes are between 13.8kV and 13.85kV.

Similarly, active-power flow in the system is described in Figures 9, 10 and 11. As can be observed, the effects of hourly variations of load profile at each node is aggregated on the branch 1, which is directly connected to the substation, producing a slight decrement on the voltage at this node, which is propagated thorough all the system and compensated by VRs at nodes 4-7 and 8-9; besides of node 12, that remains at nominal value because the reactive power compensation installed at the wind farm.

A similar conclusion could be reached by analyzing the branch currents shown in Figures 12, 13 and 14. The evolution of GA at each time step is presented in Figure 15, where is possible observing how the method has a relative fast convergence; the computational time required was 27.45 minutes; both, simulation and optimization analyzes were performed using MATLAB© computing language.

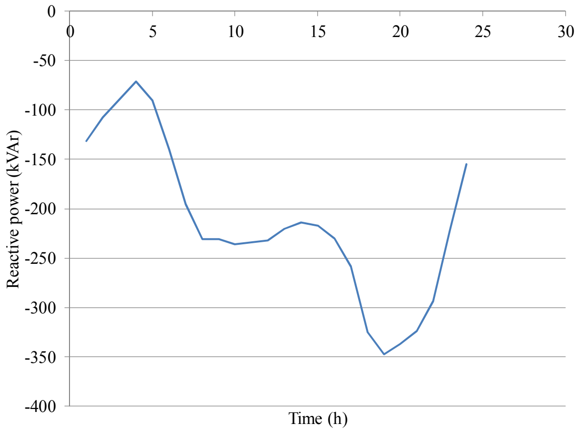

Figure 5. Reactive power injection on the node 12 (wind farm production).

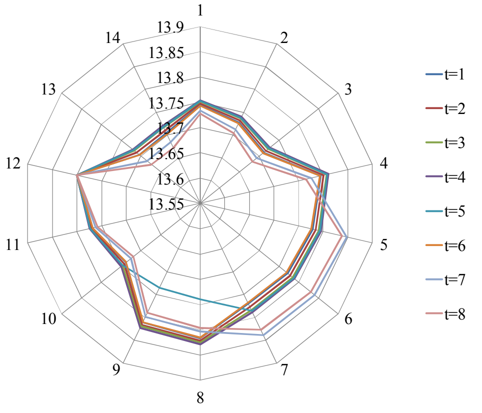

Figure 6. Voltage profile between 1h and 8h.

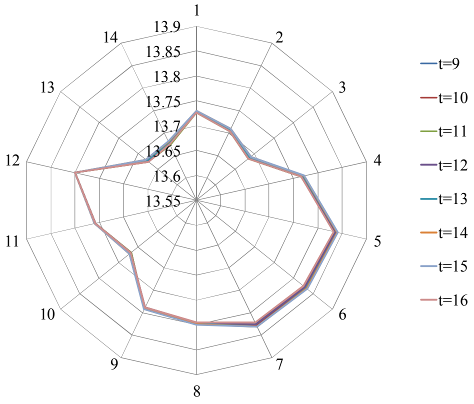

Figure 7. Voltage profile between 9h and 16h.

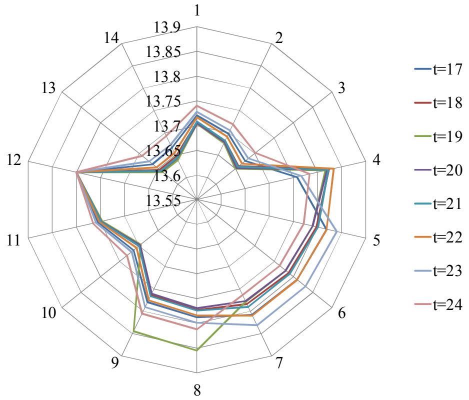

Figure 8. Voltage profile between 17h and 24h.

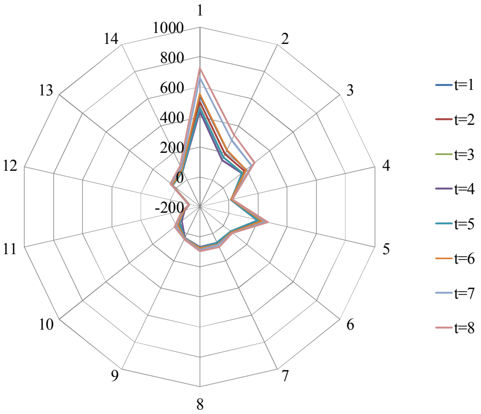

Figure 9. Active power flow between 1h and 8h.

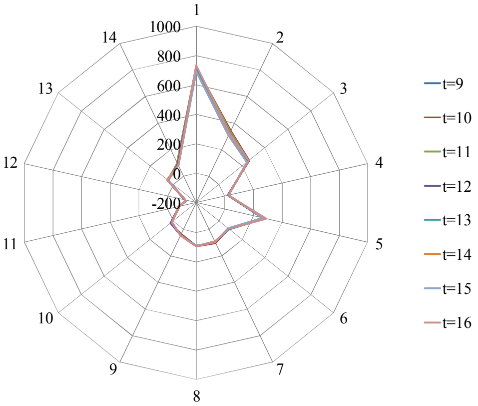

Figure 10. Active power flow between 9h and 16h.

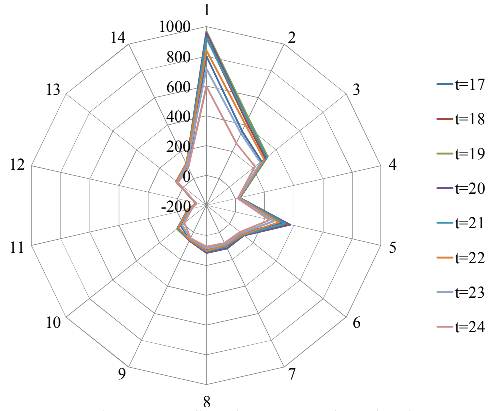

Figure 11. Active power flow between 17h and 24h.

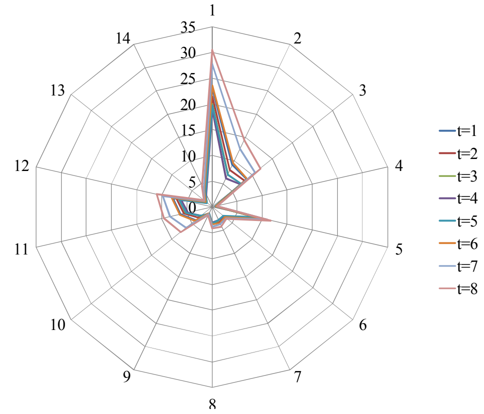

Figure 12. Branch currents between 1h and 8h.

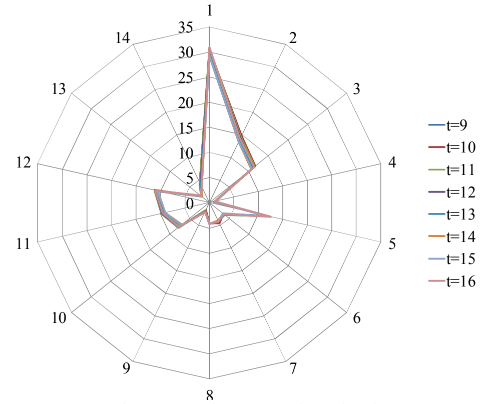

Figure 13. Branch currents between 9h and 16h.

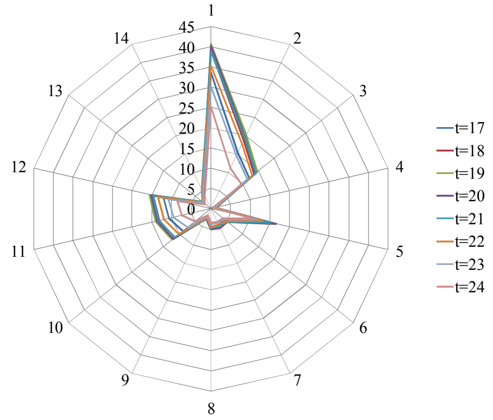

Figure 14. Branch currents between 17h and 24h.

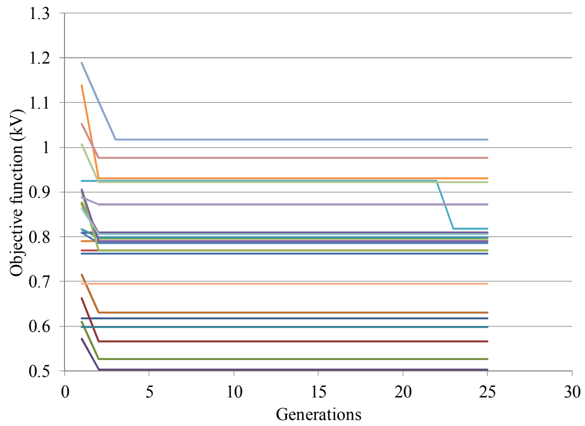

Figure 15. Evolution of GA at each time step.

IV. CONCLUSIONS

In this work, a control algorithm to improve the performance of distribution systems provided with renewable DGs, VRs, and SRPCs has been described and illustrated through a case study, considering voltage profile as a sensitive operating variable directly influenced by the hourly dynamic of load-demand and human behavior. Among several general conclusions and remarks, the proposed algorithm reveals important facts and it could be improved in many ways, some of them listed as follow: a) the presented optimization algorithm could be implemented using parallel computing in order to reduce the computational time and refine the optimization parameters; b) the joint coordination between VRs and SRPCs in day-ahead horizon could compensate the impact of variable DG on system performance and power quality; c) as the proposed method requires the treatment of a large amount of data at each relevant load-point in the system, introduction of Big Data Analytics is mandatory for the successful implementation of the presented strategy. In addition, although global optimal cannot be guaranteed by using a GA, the qualitative analysis and discussion presented during the case study verify the applicability and evaluate the performance of the proposed methodology.

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