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Smart Centralized Control System for Active Distribution Networks with Adaptive Multi-Objective Optimization

Abdelfatah Ali,[1,2] Raisz David,[2] Karar Mahmoud[3]

[1] Department of Electrical Engineering, South Valley University, Egypt,
engaaa2010@gmail.com
[2] Department of Electric Power Engineering, Budapest University of Technology and Economics, raisz.david@vet.bme.hu
[3] Department of Electrical Engineering, Aswan University, Egypt,
karar.alnagar@aswu.edu.eg

Abstract

The growth of distributed generation (DG) in distribution systems has great impacts on several practical issues, such as voltage rise/drop and system efficiency. In this paper, a smart centralized control system (SCCS) is proposed for optimizing the performance of distribution systems without violating constraints. The SCCS manages the voltage control devices (VCDs) as well as dispatchable DG sources in a cooperative manner to guarantee security and optimality of system operation. A multi-objective function with adaptive weighting factors (WFs) is introduced, which involves active losses, reactive losses, and voltage deviations. The SCCS optimizes the real-time operation of distribution systems by following a smart strategy that optimally resets the WF values as a response for violating system constraints; hence, the distribution system security is enhanced. Comprehensive simulation studies and comparisons with a time series simulation of a 24-hour period are performed to demonstrate *the efficiency of the proposed SCCS for optimizing and securing distribution systems.*

Keywords

Distributed generation (DG); distribution systems; voltage deviation; power losses; multi-objective function.

I. Introduction

The capacity of distributed generation (DG) in distribution systems has obviously increased worldwide. These DG units can be classified into dispatchable sources (e.g. diesel engines, biomass) and non-dispatchable sources (e.g. wind power, solar power) (Barros and Leite 2014), (Willis and Scott 2000). These distributed sources affect greatly the distribution system operation, control, and security (Picciariello, Alvehag, and Soder 2015; Chen et al. 2012; Viral and Khatod 2012). The dispatchable DG units with the ability to control their output power generation can play an important role in optimizing system operation under different conditions. A proper control of these dispatchable units and the available VCDs are required to avoid several potential technical problems, namely voltage rise/drop and excessive power losses.

There are two traditional control strategies for managing the distribution systems, including: 1) centralized control and 2) decentralized control (Vovos et al. 2007), (Shahraeini, Javidi, and Ghazizadeh 2011). Centralized control systems decide their control variables based on overall system information; hence, communication infrastructures are essential (Shahidehpour and Wang 2003), (Oliver Gehrke 2007). As a result, a unified control action can be performed for DGs and VCDs, such as On-Load Tap Changer (OLTCs) and step voltage regulators (SVRs). An advantage of centralized control systems is the ability of establishing coordinated control actions for all controllable devices; thus, a global optimal operation of the entire distribution system can be achieved. Furthermore, the cost of the communication devices, which are required in centralized control systems, is decreasing, and the spread of smart meters in distribution systems can be effectively employed for data transfer (Tan, Gunduz, and Poor 2013).

Several centralized control methods have been developed for managing distribution systems, whereas these methods employ optimization approaches to maximize DG benefits and keep system secure. In the literature, many methods are proposed for snapshot analysis (Cuffe and Keane 2014; Abessi, Vahidinasab, and Ghazizadeh 2015; Pilo, Pisano, and Soma 2011; Liew and Strbac 2002; Capitanescu, Bilibin, and Romero Ramos 2014; Wang et al. 2015), while other methods are applicable for real-time analysis (Alyami et al. 2014; Oshiro et al. 2011; Ziadi et al. 2014; Valverde and Van Cutsem 2013; Boehme, Harrison, and Wallace 2010). The objective functions (OFs) of the control methods could be single-objective or multi-objectives. The key single-objective functions are: 1) active loss minimization; 2) reactive loss minimization; 3) voltage deviations; and 4) cost minimization. The multi-objective functions often combine different single-objective functions, where fixed WFs are employed to setup control priorities. Since the distribution system conditions are non-predictable (e.g. load profiles and renewable DG output), the existing strategies for employing fixed WFs can neither appropriately optimize nor secure system operation (Kim and de Weck 2004).

In this paper, a SCCS is proposed for the optimal management of active distribution systems. A unified control action of the VCDs and dispatchable DG units can be handled. A multi-objective function is developed including active losses, reactive losses, and voltage deviations. Unlike the existing methods, the proposed control system is smart since it simultaneously resets the values of WFs in order to optimize the distribution system under secure operation. The main positive features of SCCS are:

- In secure operation zone (i.e. voltages within safe limits): SCCS maximizes system efficiency by optimizing the dispatchable DG units with considering mainly loss minimization in OF.
- In marginal operation zone (i.e. voltages on margin limits with the availability of VCDs control options): VCDs are employed for returning the system condition into the secure zone with maximizing system efficiency.
- In risky operation zone (i.e. voltages within marginal operation zone without VCDs control options): this zone is reached when, for example, the transformer taps reached their upper/lower limits. Under this operation, SCCS optimally resets the WFs to incorporate the voltage deviations in the optimization model. The WF values are optimally calculated for securing voltage levels (VLs) with considering system efficiency is maximized.

The advantage of SCCS is that it simultaneously resets WF values in an adaptive process in order to optimally balance between losses and voltage security. A time series simulation of a 24-hour period with a set of daily load curves is used to test SCCS.

The rest of this paper is organized as follows. Section 2 shows the adaptive multi-objective optimization. Section 3 presents the proposed solution process. Simulation results are discussed in Section 4, and conclusions are included in Section 5.

II. Problem Formulation

In this paper, the multi-objective problem is converted to a single objective optimization problem by linear combination of active losses, reactive losses, and voltage deviation objectives as follows:

$$Minimize \quad \mathrm{OF_t} = K_{PL,t}PL_t + K_{QL,t}QL_t + K_{VD,t}VD_t \tag{1}$$

$$K_{PL,t} + K_{QL,t} + K_{VD,t} = 1 \tag{2}$$

Since each time interval *t* represents 1 minute.
where :

$$PL_t = \sum_{\substack{k=1\\k=(i,j)}}^{NTL} G_k\left[V_{i,t}^2 + V_{j,t}^2 - 2V_{i,t}V_{j,t}\cos\delta_{ij,t}\right] \tag{3}$$

$$QL_t = \sum_{\substack{k=1\\k=(i,j)}}^{NTL}\left[-B_k^{sh}\left(V_{i,t}^2 + V_{j,t}^2\right) - B_k\left(V_{i,t}^2 + V_{j,t}^2 - 2V_{i,t}V_{j,t}\cos\delta_{ij,t}\right)\right] \tag{4}$$

$$VD_t = \sum_{\mathrm{i}=1}^{NB}\frac{(V_{i,t} - V_{Ni})^2}{V_{Ni}^2} \tag{5}$$

Subject to:

$$P_{Gs,t} + \sum_{i=1}^{N_{DG}} P_{DG_{i,t}} - P_{Di,t} - V_{i,t}\sum_{j=1}^{NB} V_{j,t}\left[G_{ij}\cos(\delta_{i,t} - \delta_{j,t}) + B_{ij}\sin(\delta_{i,t} - \delta_{j,t})\right] = 0 \quad \forall i \in NB, t \tag{6}$$

$$Q_{Gs,t} + \sum_{i=1}^{N_{DG}} Q_{DG_{i,t}} - Q_{Di,t} - V_{i,t}\sum_{j=1}^{NB} V_{j,t}\left[G_{ij}\sin(\delta_{i,t} - \delta_{j,t}) - B_{ij}\cos(\delta_{i,t} - \delta_{j,t})\right] = 0 \quad \forall i \in NB, t \tag{7}$$

$$V_1 = 1.0 \quad , \qquad \delta_1 = 0.0 \tag{8}$$

$$P_{Gs}^{\min} \le P_{Gs,t} \le P_{Gs}^{\max} \tag{9}$$

$$Q_{Gs}^{\min} \le Q_{Gs,t} \le Q_{Gs}^{\max} \tag{10}$$

$$V_i^{\min} \le V_{i,t} \le V_i^{\max} \quad \forall i \in NB, i \notin slack\ bus \tag{11}$$

$$P_{DG_i}^{\min} \le P_{DG_{i,t}} \le P_{DG_i}^{\max} \qquad , i = 1,2,\ldots\ldots N_{DG} \tag{12}$$

$$Q_{DG_i}^{\min} \le Q_{DG_{i,t}} \le Q_{DG_i}^{\max} \qquad , i = 1,2,\ldots\ldots N_{DG} \tag{13}$$

$$T_i^{\min} \le T_{i,t} \le T_i^{\max} \qquad , i = 1,2,\ldots\ldots NT \tag{14}$$

III. Solution Method

The interior nonlinear optimization method (Forsgren, Gill, and Wright 2002) is used in this paper to solve the OF in (1-14). It is important to note that any other nonlinear programming method can be applied to solve the optimization problem in SCCS. The optimization algorithm will be run at a time resolution of 1 minute to demonstrate the real-time operation of the distribution systems. The optimization cycle is set as 24 hour (one day) considering the daily load profile for load buses.

The proposed SCCS flowchart is shown in Figure 1. The figure shows that, firstly, time interval, taps setting, and WFs are initialized. Secondly, the system data is read. Then, the optimization problem is solved, after that the VLs are checked acceding to the following:

- If it in the ***secure*** operation zone, we go directly to the final step, where only the control action for dispatchaple DGs is performed.
- On the other hand, if it in the ***marginal*** operation zone, in this case the tap setting should be updated using (15), performing the control action for tap setting and dispatchable DG.

$$T_{i,t+1} = (1 + \Delta T_i) T_{i,t} \tag{15}$$

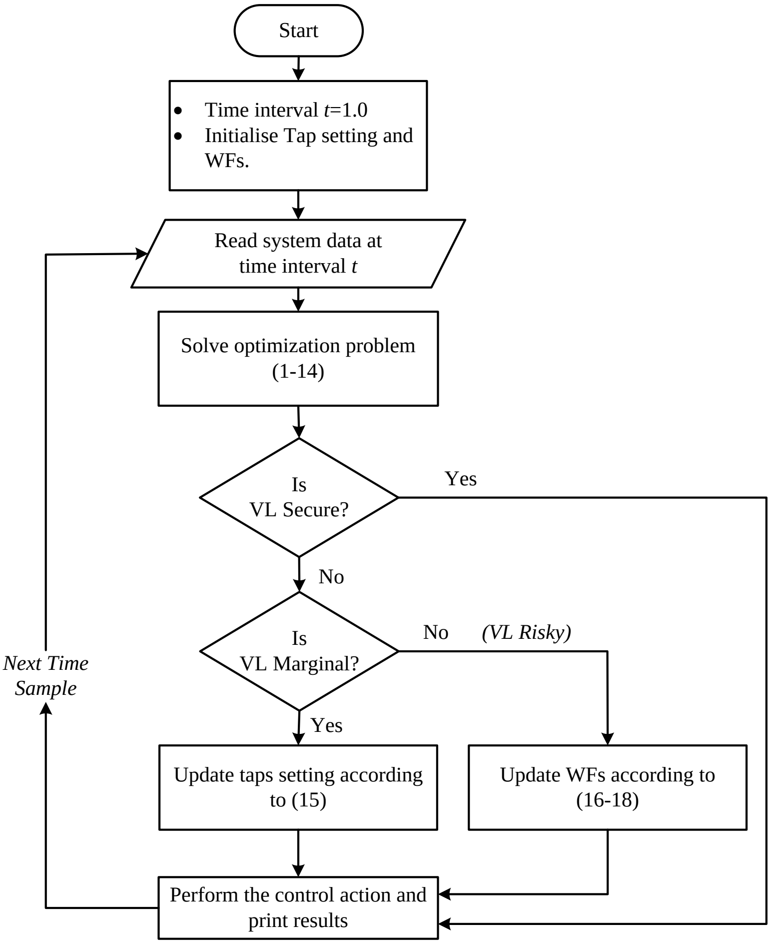

Fig. 1. Flow chart of the proposed method

in which

$$\Delta T_i = \begin{cases} +T_{i,step} & V_{i,t} < V_i^{\min} \\ 0.0 & V_i^{\min} < V_{i,t} < V_i^{\max} \\ -T_{i,step} & V_{i,t} > V_i^{\max} \end{cases}$$

- Otherwise (meaning that we are in the ***risky*** operation zone): the effectiveness of the proposed SCCS will be visible. WFs of OF optimally rests according to (16-18) to compensate voltages.

$$k_{PL,t+1} = k_{PL,t} + \Delta k_{PL} \tag{16}$$

$$k_{QL,t+1} = k_{QL,t} + \Delta k_{QL} \tag{17}$$

$$k_{VD,t+1} = k_{VD,t} + \Delta k_{VD} \tag{18}$$

After printing the results and performing control action, the algorithm goes to the next time sample and repeats the above process.

IV. Results and Discussions

The 33-bus distribution system has been used to demonstrate the effectiveness of the proposed SCCS. The complete system data are given in (Baran and Wu 1989). The 33-bus distribution system is modified in this paper in order be valid for testing SCCS. Two DGs and two SVRs are added to the system as follows:

- The two SVRs are placed at branches 6 and 25 and their tap ratios are taken as ten taps of 0.01 units from 0.95 to 1.05.
- The two DGs are connected at buses 22 and 25. They have the capability to generate both active and reactive power with maximum capacities of 0.5 MVA and 3.0 MVA, and rated capacities of 0.48 MVA and 2.7 MVA, respectively.

The real time scenarios are modelled using daily load profiles shown in Figure 2. The lower and upper voltage thresholds should be 0.95 p.u. and 1.05 p.u., respectively and these thresholds can be changed according to the region (e.g. in Europe the voltage thresholds are 0.9 and 1.1 p.u). The optimization problem described in section 2 is solved by using the student version of the AMPL solver ("A Modeling Language for Mathematical Programming" 2016).

In order to verify the positive role of the developed adaptive OF in the proposed SCCS in enhancing system performance, different three cases are studied. For all the cases, the two SVRs are employed for controlling VL. However, the control scheme of DGs, and OF setting is varied, as follows:

Case 1: This Base case is performed with the two DGs being non-dispatchable (i.e. working at their rated capacities), and OF is set to minimize losses (i.e. $k_{PL,t}$=0.5, $k_{QL,t}$=0, $k_{VD,t}$=0)

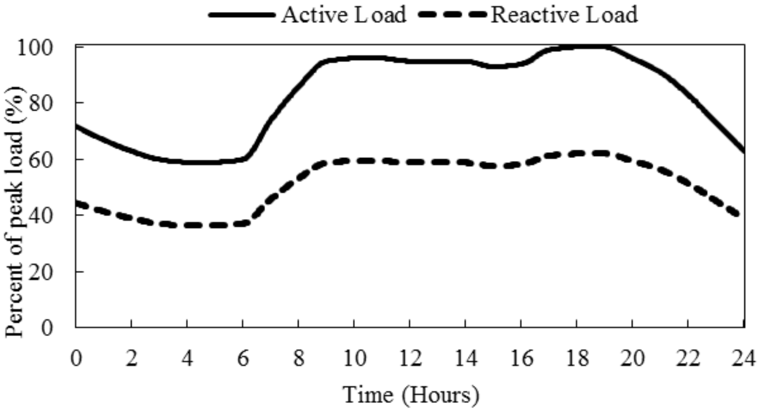

Fig. 2. Daily load profile

Case 2: The two DGs are dispatchable units; hence, their output generation can be controlled. The OF setting is the same of case 1.

Case 3: DGs are dispatchable with adaptive OF (proposed SCCS).

Case 1 represents the reference case, while case 2 has the capability to dispatch DGs. The WFs in OF for both two cases are constant, which represents several control strategies in the literature. On the contrary, the proposed SCCS (case 3) has the advantage of an adaptive OF. The simulation results of the three cases are compared, as follows

A. Voltage and Losses

This section shows the performance of the three studied cases on the voltage profile and power losses. Figure 3 shows the voltage profile for the three cases at buses 18. This bus has been selected because it is the weakest bus in the system. The total system losses are compared for the three cases in Figure 4. To facilitate discussing the figures driven by the daily load profile, the daily results are divided to three periods:

- Period T_1: From t=0 to t=16:28. The voltage during this period is in ***secure*** operation zone.
- Period T_2: From t=16:29 to t=20:30. The VL during this period is in ***risky*** operation zone, where one of the SVR taps reached to its maximum limits. Under this operation, SCCS in case 3 will optimally reset the WF values to compensate voltages.
- Period T_3: From t=20:31 to t=24:00. The voltage during this period is in ***secure*** operation zone.

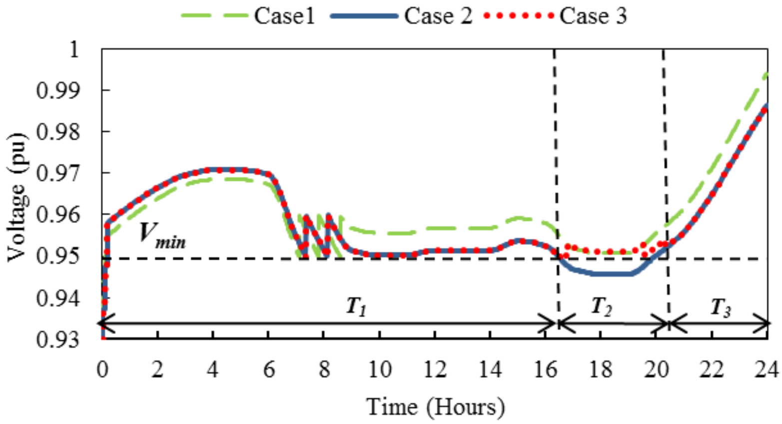

Fig. 3. Daily voltage profiles at bus 18

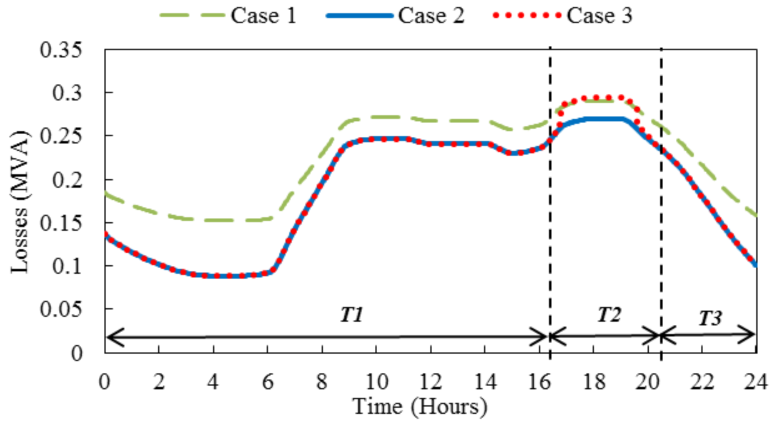

Fig. 4. Total losses

For the first case, case 1, the voltage profile never goes out of its limits as shown in Figure 3, as the output powers from DGs are high and lead to raised VL. However, the voltage at bus 18 during T_2 is considered in the ***risky*** operation zone. The losses in this case are very high during the day, as shown in Figure 4. The reason for these excessive losses is that DGs are not dispatchable. Regarding the second case, case 2, the voltage at bus 18 violated the lower limit during the period T_2. This is driven by the fact that the SVR at branch 6 reached its maximum position at T_2, so it could not prevent the voltage at bus 18 from getting out of its limits.

On the other side, the losses are greatly improved. This is occur as OF is set to only power losses. Finally, both voltage profile and losses are improved using the proposed SCCS (i.e. case 3). The voltage has been successfully compensated during the ***risky*** period T_2 as a result of the operation of the adaptive OF algorithm. Another advantage of the proposed SCCS is that the loss profile is the same as in case 2, except a slightly increase during T_2 as a result of decreasing the WF values of the losses and the increase of WF value for the voltage deviations. These results show the benefit of the proposed adaptive OF in SCCS, where it has the ability to keep the voltage within the desired ***secur***e zone without excessively increasing the losses.

B. Tap changer Operation and DG outputs

Although the traditional method and the proposed method can achieve similar voltage regulation performance, the proposed SCCS method with adaptive objective function can regulate the voltages when the SVR fails to overcome it. Figure 5 and Figure 6 show the SVR daily tap positions comparison under three cases. In Figure 5, the minimum and maximum SVR tap positions at branch 6 are 1.0 and 1.05, respectively in all cases. We can note that the SVR reached its maximum position. However, it was unable to prevent the voltage at bus 18 from violating the limits in case 2 as described before. The minimum and maximum SVR tap positions at branch 25 are 1.0 and 1.04, respectively in all cases as shown in Figure 6. We note that the SVR don’t reach its maximum position. However, it was able to preserve the voltages within limits during three cases. Moreover, the SVR at branch 6 has 5 tap changing operations and the SVR at branch 25 has only 4 tap changing operations. The daily power generation of DGs mix for the 33-bus system is shown in Figure 7 and Figure 8.

Case 1 shows the outputs of the non-dispatchaple DG units which work at their rated outputs during the three periods. The daily power outputs of the dispatchable DG units are shown in case 2, these curves follow the load demand pattern and obtained using a computational optimization algorithm described in Section 3. The output power in case 3 is the same as case 2 except during the period T_2, DG connected by bus 22 has output power equal to its rated capacity, while DG connected by bus 25 operated with output power more than its rated capacity, but less than the maximum capacity to overcome voltages shortage during this period.

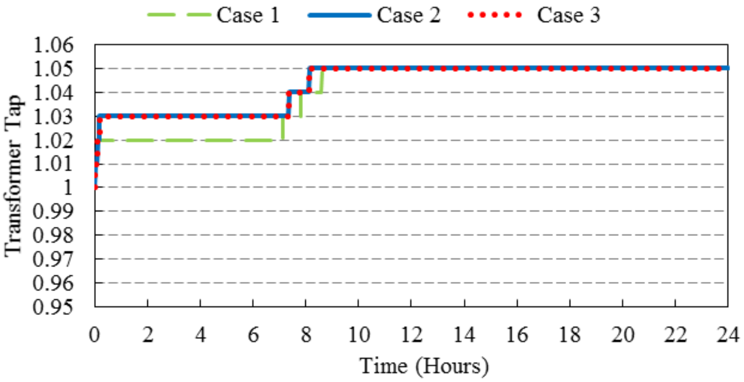

Fig. 5. Transformer tap steps at branch 6

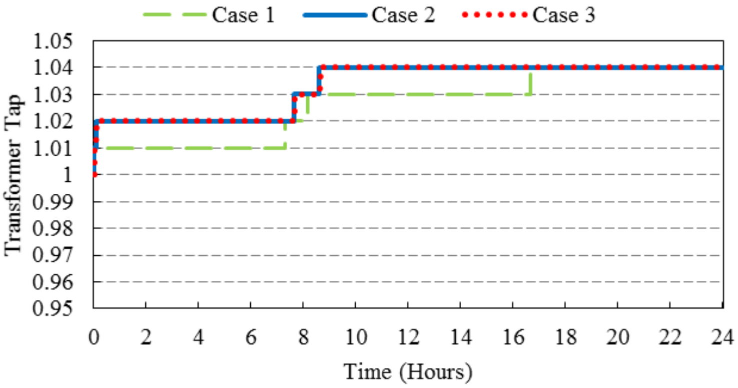

Fig. 6. Transformer tap steps at branch 25

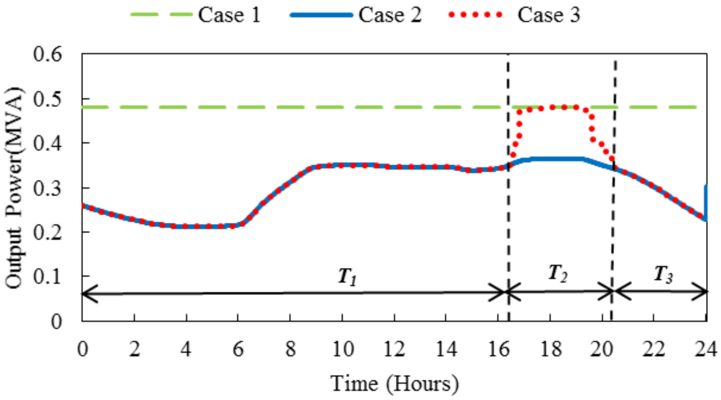

Fig. 7. Daily power generation of DG units at bus 22

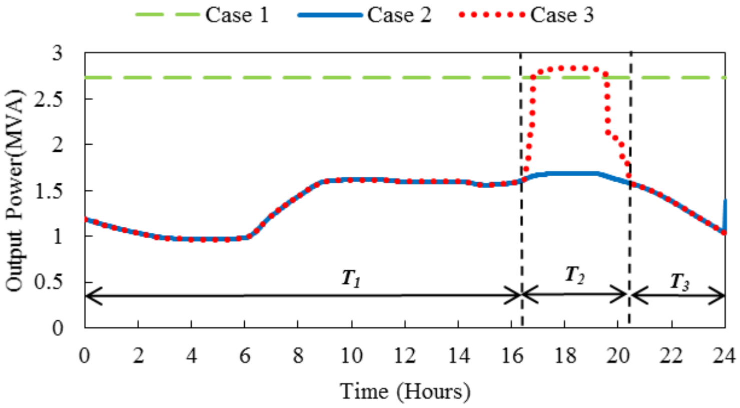

Fig. 8. Daily power generation of DG units at bus 25

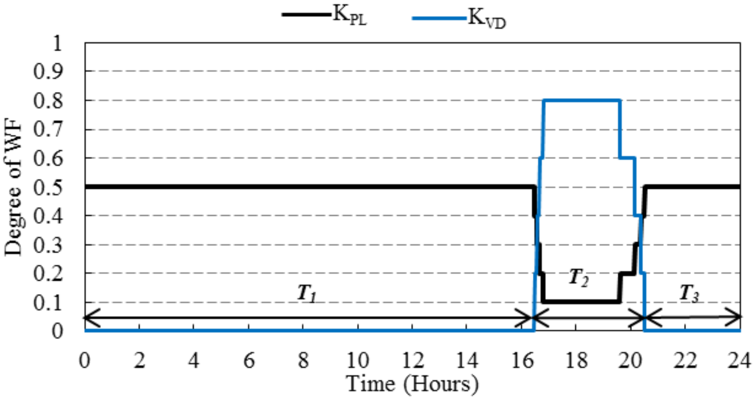

Fig. 9. WFs changing

The changing of different WF values is illustrated in Figure 9. The WFs of active and reactive power losses are assumed to be equal, so only active power losses and voltage profile WFs are shown. The figure shows that the value of k_{PL} during periods T_1 and T_3 is fixed at 0.5, while k_{VD} value is fixed at zero. During the period T_2 (when voltages violate the limits), the values of k_{PL}, k_{QL} and k_{VD} were changing, where k_{VD} value was increasing and k_{PL} value was decreasing. In this case the priority will be for the voltage deviation OF to overcome violation limits problem when the SVR fails. K_{PL} decreased until 0.1 and k_{VD} increased until 0.8. After overcoming the problem and the system voltage profiles are in secure zone, the WFs k_{PL} and k_{VD} are returned back to their initial values.

V. Conclusions

This paper proposed SCCS for optimally managing distribution systems. The proposed control scheme adopts multi-objective function with considering system constraints. The proposed control system is efficient, since it simultaneously resets WF values, according to the system condition. A unified control action of dispatchable DG units and VCDs are applicable for the purpose of securing and optimizing system performance. The effectiveness of the proposed SCCS is demonstrated through simulating daily operation of the 33-bus distribution system. The simulation results demonstrate that SCCS can guarantee optimal system operation (i.e. loss minimization) during normal system operation, and secure system operation at ill-conditions. Unlike the fixed OF optimization, the proposed adaptive OF optimization offers further control action to keep VL in its desired normal zone. In the future, different components of distribution systems will be considered, such as energy storage devices and capacitor banks.

Symbols

OF_t: Objective function at time interval *t*
PL_t: Total active power losses at time interval *t* (MW)
QL_t : Total reactive power losses at time interval *t* (Mvar)
VD_t : Total voltage magnitude deviation of the power system at time interval *t*
$k_{PL,t}$: Weighing factor of active power losses at time interval *t*
$k_{QL,t}$: Weighing factor of reactive power losses at time interval *t*
$k_{VD,t}$: Weighing factor of voltage deviation at time interval *t*
$\Delta T_i, \Delta k_{PL}, \Delta k_{QL}, \Delta k_{VD}$: Constants
$k_{PL,step}$: Active power losses WF changing step
$k_{QL,step}$: Reactive power losses WF changing step
$k_{VD,step}$: Voltage deviation WF changing step
P_{Gs} : Active power output of slack bus (MW)
Q_{Gs} : Reactive power output of lack bus (Mvar)
$P_{Gs}^{\max}$: Maximum active power output of slack bus (MW)
$P_{Gs}^{\min}$: Minimum active power output of slack bus (MW)
$Q_{Gs}^{\max}$: Maximum reactive power output of slack bus(Mvar)
$Q_{Gs}^{\min}$: Minimum reactive power output of slack bus (Mvar)

P_{Di} : Active load demand of i^{th} bus (MW)
Q_{Di} : Reactive load demand of i^{th} bus (Mvar)
P_{DG_i} :DG active power output at i^{th} bus (MW)
Q_{DG_i} : DG reactive power output at i^{th} bus(Mvar)
$P_{DG\ i}^{\max}$:Maximum DG active power output at bus i (MW)
$P_{DG\ i}^{\min}$:Minimum DG active power output at bus i (MW)
$Q_{DG\ i}^{\max}$:Maximum DG reactive power output at bus i (Mvar)
$Q_{DG\ i}^{\min}$:Minimum DG reactive power output at bus I (Mvar)
$T_{i,t}$: Transformer taps settings of i^{th} transformer at time interval t (p.u.)
$T_i^{\max}$:Maximum tap settings limit of i^{th} transformer (p.u.)
$T_i^{\min}$: Minimum tap settings limit of i^{th} transformer (p.u.)
$T_{i,step}$: Tap step of i^{th} transformer
V_1 :Voltage of slack bus (p.u.)
V_i : Voltage of i^{th} bus (p.u.)
V_{Ni} : Nominal voltage of i^{th} bus (p.u)
$V_i^{\min}$:Minimum load voltage of i^{th} bus (p.u.)
$V_i^{\max}$: Maximum load voltage of i^{th} bus (p.u.)
G_{ij} : Conductance between bus i and bus j (p.u.)
B_{ij} : Susceptance between bus i and bus j (p.u.)
B_k^{sh} : Shunt susceptance of the branch k
δ_i :Voltage angle at i^{th} bus (Rad)
δ_1 : Voltage angle at slack bus
NB: Number of buses
NTL :Number of transmission lines
N_{DG} : Number of buses connected with DG units
NT : Number of tap regulating transformers

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