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Abstract

In modern medium voltage distribution grids, voltage and reactive power (Volt/VAr) control can effectively be achieved using the time delayed responses of on-load tap changer, line voltage regulators, capacitor banks and distributed generation (DG) units. The timely coordination among different Volt/VAr control (VVC) devices can be assured through online control processes and updating the control parameters (i.e. set-points) of VVC devices. This is essential for efficient operation of the distribution grids while achieving steady-state voltage recovery and other control objectives such as loss minimisation; as the control interactions among VVC devices and Volt/VAr support DG units caused by poor coordination can lead to operational conflicts. In this article, a novel control approach is proposed for updating VVC set-points for eliminating operational interactions between different voltage regulating devices; thereby, minimising power losses in a network. The proposed strategy has been tested on a practical distribution system derived from the state of New South Wales, Australia, and the simulation results are reported. The results have demonstrated that the interactions among VVC devices and Volt/VAr support DG units can be avoided while minimising power losses, with the implementation of the proposed strategy.

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Novel Strategy of Updating Volt/VAr Control Set-points for Eliminating Interactions between Different Voltage Regulating Devices and DG Units

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ABSTRACT

In modern medium voltage distribution grids, voltage and reactive power (Volt/VAr) control can effectively be achieved using the time delayed responses of on-load tap changer, line voltage regulators, capacitor banks, and distributed generation (DG) units. The timely coordination among different Volt/VAr control (VVC) devices can be assured through online control processes and updating the control parameters (i.e., set-points) of VVC devices. This is essential for efficient operation of the distribution grids while achieving steady-state voltage recovery and other control objectives such as loss minimisation; as the control interactions among VVC devices and Volt/VAr support DG units caused by poor coordination can lead to operational conflicts. In this paper, a novel control approach is proposed for updating VVC set-points for eliminating operational interactions between different voltage regulating devices; thereby minimising power losses in a network. The proposed strategy has been tested on a practical distribution system derived from the state of New South Wales, Australia, and the simulation results are reported. The results have demonstrated that the interactions among VVC devices and Volt/VAr support DG units can be avoided while minimising power losses, with the implementation of the proposed strategy.

1. Introduction

The concept of voltage and reactive power (Volt/VAr) control is a fundamental requirement for delivering electric power (a) within appropriate voltage limits (stipulated by technical standards) in such a way that consumers' equipment operate flawlessly, and (b) by maintaining load power factor close to unity. The relationship between voltage and reactive power varies based on the type of load, system topology, Volt/VAr controllers' parameters i.e., set-points and their modes of operation, level of local generation, and the location of distributed energy resources. On the other hand, the smart grid concept has dramatically changed the design and operation of Volt/VAr control (VVC) devices in modern distribution systems. The objectives of VVC have expanded considerably beyond simply maintaining acceptable voltage and power factor. To the current context, the main objective is to achieve Volt/VAr optimisation, which has evolved over a period of time through stand-alone control, rule-based control using supervisory control and data acquisition (SCADA), advanced analytics-based control, and model-driven control using distribution management system (DMS). Consequently,

the main operational objectives in modern distribution systems are to minimise losses, increase overall system efficiency, reduce operational cost, implement demand side management, promote energy conservation, and improve power quality and voltage stability margin. The details of stand-alone VVC methods can be found in (Kersting 2002; Pahwa et al. 2014). In (Elkhatib, Shatshat, and Salama 2011; Alobeidli and Moursi 2014; Moursi et al. 2014), some of the rule-based controls enabled with or without SCADA are detailed; whereas advanced analytics-based VVC and DMS model-driven methods can be found in (Akagi et al. 2016; Augugliaro et al. 2004). In (Ding et al. 2016; Yamamoto et al. 2014; Malekpour and Niknam 2011), some of the modern optimal VVC methods applicable to balanced and unbalanced distribution systems embedded with distributed generation (DG) are detailed.

Modern VVC systems must accommodate distributed energy resources and respond automatically when changes occur in the status or output level of these resources. In addition, these control systems should operate effectively following feeder reconfigurations which may happen more frequently in a modern distribution grid due to optimal

network reconfiguration, automatic service restoration, DG availability and other applications involving smart switching. Moreover, utilisation of DG units for system Volt/VAr support with different operational modes, in coordination with other voltage regulating devices such as on-load tap changer (OLTC), line voltage regulators (VRs) and capacitor banks (CBs), is emerged as one of the viable options for increasing the hosting capacity of distributed energy resources in distribution systems. Therefore, it is clear that the complex and inherently varying nature of modern distribution systems make the task of managing and operating such systems more challenging thereby adversely affecting conventional VVC.

Presently, DMS-model based optimal VVC is dominant. Many research studies and pilot-projects are being carried out in academia and industry all over the world. It is noted that loss minimisation is still one of the fundamental objectives of VVC under multi-objective scenarios. The tuned VVC set-points can possibly be updated simultaneously and/or non-simultaneously by the network operator as the Volt/VAr controllers are equipped with assigned control logic or algorithms, controller limits and fixed time-graded operation (Viawan 2008). However, even though the optimisation algorithm is capable of modelling many system phenomena and accordingly solving the formulated problem, it is still unclear whether or not the associated controls can fully achieve the intended coordinated operations in reality under inherently varying system conditions accompanied with modern distribution system operation. In (Viawan and Karlsson 2007), it is highlighted that the objectives associated with the optimal VVC may not be fully achieved under certain system conditions due to the conflicting operations caused by steady-state interactions among multiple voltage regulating devices and the Volt/VAr support DG units. Even though the formulation is further enhanced to tackle the coordinated operation; the assigned time-graded operation for VVC devices also may not be capable enough to guarantee the desired coordinated operation under all system conditions, since inherently varying distribution system characteristics are difficult to predict accurately in the presence of Volt/VAr support DG units (Yamamoto et al. 2014). Moreover, centralised control over DG will depend on many factors such as operation of manufacturer inbuilt controls and associated limiters, communication infrastructure, and manageability of DG units with weather and generation forecasting; which lead to complex implementation issues. Even though the tuned controller parameters i.e., set-points are updated simultaneously, the above mentioned factors may delay the VVC responses from DG units in presence of inherently varying system conditions thereby resulting into interactions among DG units and other voltage regulating devices; since there is no mechanism to ensure the coordinated operation after the post-optimisation stage. These issues can be resolved

with the aid of model predictive control approaches and performance coordination using DMS functionalities as detailed in (Valverde and Cutsem 2013). However, the real-world operation of such process controls in electric power distribution systems may sometimes be cumbersome as pointed out in (Jiang et al. 2016). Moreover, there would be modifications in the local controllers of voltage regulating devices and Volt/VAr support DG units for ensuring the intended coordinated operation; which are not explicitly addressed in literature that utilise conventional DMS tasks for implementing the proposed controls.

Grid interactions can lead to conflicting operations under certain system conditions also causing significant transients and oscillations in the system as detailed in (Ranamuka, Agalgaonkar, and Muttaqi 2017). The resultant adverse effects can appear in the form of performance deteriorations in the adopted VVC and system protection schemes and overall system reliability.

The comprehensive literature review suggests that deployment of optimal VVC in modern distribution systems requires greater attention and mechanisms for avoiding possible grid interactions while achieving stipulated control objectives. The main contributions of this paper include addressing steady-state interactions among VVC devices and Volt/VAr support DG units; and development of a novel online control strategy for timely updating the VVC set-points for eliminating possible grid interactions in operational states targeted to power loss minimisation. In the proposed method, the control set-points of VVC devices and DG units are updated via substation centered DMS, while ensuring the intended coordinated operation of devices under varying system conditions. Sequential quadratic programming (SQP) is applied for loss minimisation depicting an example case; while explicit focus of the paper is on eliminating the possible steady-state interactions. Moreover, associated interactions among multiple voltage regulating devices and Volt/VAr support DG units are examined through time domain simulations with a detailed model of a practical test distribution system. The proposed control strategy is validated using several case studies. A special consideration is given to the synchronous machine based DG units, since the DG units embedded in Australian medium voltage (MV) distribution systems are mainly based on synchronous machine based technologies. The rest of the paper is structured as follows. In Section-2, the proposed research strategy is presented. Section-3 presents the test case study and simulation results. The conclusions are included in Section-4.

2. Proposed Strategy

In this section, the proposed strategy for updating VVC set-points for eliminating grid interactions in operational states

targeted to power loss minimisation is presented. The VVC set-points are derived with an objective of loss minimisation using SQP, considering hourly control-states as mentioned in Section 2.1. The mathematical formulation considers the availability of forecast of load demand, initial tap and CB switching positions and DG power output in the form of time series data. The control approach proposed for coordinating the VVC devices in order to eliminate possible grid interactions in each hourly control-state along with the pseudo-code is detailed in Section 2.2. Figure 1 shows the topology of overall control approach. These controls are proposed to enact using substation centered advanced DMS.

Figure 1. Overall topology of the proposed control approach

2.1 Deriving VVC Set-Points

Since a substation OLTC deals with voltage regulation at the substation bus-bar level using a coarse control and operates after a prolonged time delay, the substation OLTC operation is not considered as a control variable (Ranamuka, Agalgaonkar, and Muttaqi 2014; Ranamuka, Agalgaonkar, and Muttaqi 2016). The total number of buses in the distribution system are denoted by n (i.e., $i = 1, \dots, n$), where similarly total number of DG units and CBs are denoted by k and h , respectively. The generic form of the problem is given by (1). It is subjected to deriving control variables i.e., voltage reference values for tap changing devices, $V_{ref/svrm}$, VAr reference values for DG units, $V_{ref/dgk}$ ($=Q_{dgk}$) and VAr reference values for CBs, $V_{ref/cbh}$ ($=Q_{cbh}$), while satisfying equality and inequality constraints denoted by g and h , respectively. The equality constraints are active and reactive power balance equations. The Q_{dgk} and Q_{cbh} denote reactive power supply from k^{th} DG unit and h^{th} CB, respectively. The considered inequality constraints are: voltage limits, hourly DG reactive power capability limits, distribution line thermal limits, transformer capacity limits, tap limits of VRs, and VAr limits of CBs.

The search-direction at current iterate, k is denoted by $d^{(k)}$. The ∇f denotes respective gradient matrix of the objective function, f of the vector of variables $x^{(k)}$ including control variables; while $\nabla^2 L$ denotes the matrix of Hessian of the respective Lagrangian (positive definite approximation). It is a matrix of second order derivatives of the objective function,

$f(x^{(k)})$ and the components of equality constraints functions, $g(x^{(k)})$ and non-equality constraints functions, $h(x^{(k)})$ in addition to the Lagrangian multipliers, $\lambda^{(k)}$. The Lagrangian of this problem is given by (2). It is noted that the Lagrangian multipliers of the equality constraints must be non-negative. The Jacobian matrices corresponding to the constraints vectors of equality and non-equality constraints functions are J_g and J_h , respectively. Handling discrete control variables is done following the method proposed in (Kulmala, Repo, and Jarventausta 2014). Also, it is worth noting that the discrete control variables related to CB switching operations can also be treated as tap operations. In this paper, CB switching operations are assumed as continuous control variables in the loss minimisation process. It is mainly because (a) the operational cost associated with a VAr supply from CB is normally very small, and (b) the impact of a CB switching operations on system voltage is localised. The methodology and algorithm proposed in (MATLAB Central-MathWorks 2014) is used for solving the quadratic sub-problem in MATLAB.

$$\min_{d^{(k)}} (\nabla f)^{(k)T} d^{(k)} + \frac{1}{2} d^{(k)T} (\nabla^2 L)^{(k)} d^{(k)}$$

$$\forall \quad g^{(k)} + J_g^{(k)} d^{(k)} = 0, \quad h^{(k)} + J_h^{(k)} d^{(k)} \leq 0 \quad (1)$$

$$L(x^{(k)}, \lambda^{(k)}) = f^{(k)} + \sum \lambda_g^{(k)} g^{(k)} + \sum \lambda_h^{(k)} h^{(k)} \quad (2)$$

If the DG units and CBs are operated in voltage control mode, the respective control variables will be $V_{ref/dgk}$ and $V_{ref/cbh(ON)/V_{ref/cbh(OFF)}}$; and accordingly, the problem needs to be re-formulated. The set voltage reference value for a DG controller is denoted using $V_{ref/dgk}$, where the set voltage reference values for a CB controller switch-on and switch-off status are denoted using $V_{ref/cbh(ON)}$ and $V_{ref/cbh(OFF)}$, respectively. Moreover, the voltage control device manoeuvres can be minimised by appropriately maintaining lower values for voltage limits (i.e., V_{min} and V_{max}) compared to the substation secondary bus voltage. It is assumed that the derivation of hourly DG reactive power capability limits in accordance with the availability of DG active power generation (P_{dgk}) in each hourly control-state is carried out by an algorithm embedded in the DMS, and the loss minimisation algorithm is updated accordingly. The derivation of reactive power capability limits for different types of DG units considering the operational aspects and associated controller limitations is detailed in (Caldon, Rossetto, and Scala 2003; Zou et al. 2012).

Figure 2. Topology of control strategy proposed for eliminating grid interactions

2.2 Coordinating VVC Devices

The topology of the event triggered control strategy proposed for coordinating VVC devices in order to eliminate possible grid interactions is shown in Figure 2, where the pseudo-code summarises the control mechanism. SCADA, RTU and AMI denote supervisory control and data acquisition, remote terminal unit and advanced metering infrastructure, respectively. For the subsequent operations; the time delay sequence of multiple VRs, $T_{VR(i)}$ are maintained as given by (3). The VRs (i.e., $i = 1, \dots, n$) are counted from substation end. T_{DG} and T_{CB} denote the time delays associated with DG and CB unit operations. The voltage reference values (in pu) for tap-changing devices (such as VRs) are derived using (4) and the tap ratio values, a_{svrm} obtained using loss minimisation algorithm. The per-unit value of voltage changed by one tap operation is denoted by V_{tap} , where the time at the beginning of each control state is denoted by t_o . Therefore, $V_{ref/tap|t_o}$ and $a_{svrm|t_o}$ represent the voltage reference value and tap ratio at time, $t=t_o$, respectively. The binary [0, 1] module, β is integrated for externally controlling the tap changer local control actions by appropriately operating MOD-T module. The operation of MOD-T is given under Tap Changer Control-Model.

$$T_{VR(1)} < T_{VR(2)} < \dots < T_{VR(i)} < \dots < T_{VR(n)} \quad (3)$$

$$\forall T_{VR(i)} \gg T_{DG}, T_{CB}$$

$$V_{ref/tapchanger} = \begin{cases} V_{ref/tap|t_o} + \sum \Delta V_{tap}; & \text{if } Tap \uparrow \\ V_{ref/tap|t_o} - \sum \Delta V_{tap}; & \text{if } Tap \downarrow \end{cases} \quad (4)$$

$$\forall \sum \Delta V_{tap} = \text{mod} \left(a_{svrm} - a_{svrm|t_o} \right) \times V_{tap}$$

The local control actions of DG-excitation, tap changer and CB controls are adopted from (Kundur 1994; Choi and Kim 2001; Freitas et al. 2005; Muppatty 2011). The modifications required in local controllers of VVC devices and Volt/VAr support DG units for accommodating the proposed strategy are given below in conjunction with the pseudo-code representation of the control mechanism. It is one of the integral parts of the proposed strategy presented in this paper. Those modifications are compatible to local control models used for representing the VVC devices.

Pseudo Code:

- **Step-I:** Start
- **Step-II:** Reset, initialise and set set-time for hourly control state (i.e., $t=3600$ s) of the timer
- **Step-III:** Execute hourly settings i.e., $V_{ref/svrm}$, $VAR_{ref/dgk}$, $VAR_{ref/cbh}$ from loss minimisation module

If $VAR_{ref/dgk}$ and/or $VAR_{ref/cbh} = VAR_{ref/dgk}$ and/or $VAR_{ref/cbh} \mid t < 0$;
 Go to Step-VI
 else Go to Step-IV

end
- **Step-IV:** Update $VAR_{ref/dgk}$ and/or $VAR_{ref/cbh}$
- **Step-V:** Execute information from control events triggered in control system (1.): DG local control (i.e., excitation control in case of synchronous machine based DG units) and (2.): CB local control

If $Q_{dgk} \approx VAR_{ref/dgk}$ and/or $Q_{cbh} \approx VAR_{ref/cbh}$;
 Go to Step-VI
 else Go to Step-VII

end
- **Step-VI:** Enact the operation of tap-changing devices

If $V_{ref/svrm} = V_{ref/svrm} \mid t < 0$;
 Go to Step-VIII
 else Go to Step-VII

end
- **Step-VII:** Update $V_{ref/svrm}$
- **Step-VIII:** Update $\beta=1$
- **Step-IX:** Execute information from set-time reach event triggered in a timer circuit

If $t=3600$ s;
 Update $\beta=0$
 else Go to Step-IX

end
- **Step-X:** Stop

Tap Changer Control-Model:

The dead-band and hysteresis band are denoted by DB and ϵ , respectively. The tap-changer controller time delay is T_d , where its total mechanical time delay is T_m . The $\delta(t-T_m)$ denotes T_m time-delayed unit impulse function in time, t -domain (Kundur 1994; Choi and Kim 2001). Other notations are referred to Figure 2.

- **Step-I:** Start

- **Step-II:** Execute control signal from Step-VII of the proposed controls (pseudo-code); Go to Step-III

- **Step-III:** In-built controls

$$V_{err} = V_{ref/tapchanger} - V_C$$

$$V_m = \begin{cases} 0 & \text{for } -DB \leq V_{err} \leq +DB \\ 0 & \text{for } +DB < V_{err} \leq +DB + \epsilon; \quad V_{err} \uparrow \\ 0 & \text{for } -DB - \epsilon \leq V_{err} < -DB; \quad V_{err} \downarrow \\ +1 & \text{for } V_{err} > +DB + \epsilon \\ +1 & \text{for } +DB < V_{err} \leq +DB + \epsilon; \quad V_{err} \downarrow \\ -1 & \text{for } V_{err} < -DB - \epsilon \\ -1 & \text{for } -DB - \epsilon \leq V_{err} < -DB; \quad V_{err} \uparrow \end{cases}$$

- **Step-IV:** Newly added controls (MOD-T)

MOD - T:

$$V_t = \begin{cases} V_m & \text{if } \beta = 1 \\ 0 & \text{if } \beta = 0 \end{cases}$$

- **Step-V:** In-built controls

$$\begin{aligned} T &= T + \Delta t & \text{if } V_t \neq 0 \\ T &= 0 & \text{if } V_t = 0 \\ T &= 0 & \text{if } V_N \neq 0 \\ T &= 0 & \text{if } V_t \text{ changes } \pm \end{aligned}$$

$$\begin{aligned} \text{if } T \leq T_d; \quad V_d &= 0 \\ \text{if } T > T_d; \quad V_d &= V_t \end{aligned}$$

- **Step-VI:** In-built controls (motor and drive unit)

$$V_N = \delta(t - T_m) \times V_d$$

- **Step-VII:** Execute the control signal form Step-IX of the proposed controls (pseudo-code); Go to Step-VIII

- **Step-VIII:** Stop

Capacitor Bank Control-Model:

The considered control algorithm for CB control-model is outlined below, and it is a modified version of controls in (Muppatty 2011).

- **Step-I:** Start

- **Step-II:** Execute control signal from Step-IV of the proposed controls (pseudo-code) and terminal voltage, V ; Go to Step-III

• **Step-III:** Modified in-built controls

.....
 If $Q_{cbh} < VAr_{ref} / cbh$ or $Q_{cbh} > VAr_{ref} / cbh$
 Go to Step – IV
 else Go to Step – II
 end

• **Step-IV:** In-built controls (check for zero-voltage, $V(0)$ instant)

.....
 If $V(0)$ is detected
 Go to Step – V
 else Go to Step – IV
 end

• **Step-V:** Modified in-built controls (enact CB switching operations)

.....
 Initialise open or close signal $\downarrow$
 Apply time delay $\forall \Delta T_c \downarrow$
 Switch open or close until $Q_{cbh} \approx VAr_{ref} / cbh \downarrow$
 Go to Step – VI

Step-VI: Stop

DG Excitation Control-Model:

The excitation system model detailed in (Ranamuka, Agalgaonkar, and Muttaqi 2017; Freitas et al. 2005) can be used for simulating the DG excitation control (i.e., the highlighted circuit part in Figure 2). Its topology is shown in Figure 3. The T and S and/or K values in each block (as depicted in Figure 3) define the respective time delays and gain constants in the circuit, where s denotes the Laplace transform operator.

Figure 3. Block diagram of excitation system model

This control strategy will work well for a system under normal-state operation avoiding steady-state control interactions among the VVC devices and resultant conflicting operations. It is because the load ramping during an hourly

period will not violate the stipulated voltage limits in the system with hourly based update in the control set-points of VVC devices. The test case study presented in Section 3 demonstrates the merits of the proposed strategy. In addition to the capability of eliminating possible Volt/VAr support DG and voltage regulating device interactions, the simulation results reveal that the proposed methodology is also capable of significantly minimising the reactive power import from the transmission systems, which will greatly support the Volt/VAr management in the power system.

3. Test Case Study and Validation

In this section, results of the test case studies are presented. Topology of the MV test distribution feeder system is shown in Figure 4. It is fed by a 132/11 kV, 30 MVA transformer, and it includes 123 nodes. Among different feeder system configurations, the simulation results on feeder configuration-01 are presented in this paper. The balanced distribution feeder system operation with two renewable synchronous machine based DG units, i.e., DG1 and DG2 with 0.750 MVA rated capacity each is used for the simulation purposes. The capacitor bank, CB1 is of 0.500 MVar capacity (with 10 equal switching steps).

Accordingly, the different system states have been modeled and simulated depicting the distribution system operation. The case studies presented in this section are based on a daily operation of the distribution system considering hourly control states. MATLAB and Simulink software are used for modelling and simulations.

Figure 5 (a) depicts the simulated load demand pattern, where the load demand values are in per unit. The simulated per unit active power generation patterns for DG1 and DG2 are shown in Figure 5 (b). The loss minimisation model given by (2) is adopted for deriving the control parameters (i.e., control set-points) of the VVC devices. The simulated substation secondary bus voltage is 1.03 pu; while feeder bus voltage limits are maintained within 0.90 pu and 1.04 pu, thereby also minimising voltage control device manoeuvres. For Type-B type VRs, 32 tap positions (+16/-16) are modeled and magnitude of voltage correction for one tap operation equals to 0.00625 pu without LDC.

3.1 Simulation Case Study-1

In this section, the simulated results for the test distribution system adopting the loss minimisation algorithm (i.e., without incorporating the strategy for eliminating grid interactions) is compared with the simulated results under unregulated system where VAr support from DG units = 0, VAr supply from CBs = 0 and tap position for VRs = 1. The derived hourly control set-points for VRs and DG units are shown in Figures 6 (a) and (b), respectively.

Figure 4. Topology of the MV test distribution feeder system

Figure 5. Simulated (a) daily load demand pattern of the test distribution system, and (b) active power generation patterns for DG1 and DG2

Figure 7 (a) shows the active power losses for the unregulated system and for the system operated with the loss minimisation process; whereas Figures 7 (b) and (c) show the voltage at selected buses for unregulated and regulated systems, respectively. Figure 7 (d) shows the reactive power imported from transmission systems under unregulated and regulated systems. It can be seen that the power losses including reactive power imported from transmission systems are significantly reduced under example Volt/VAr optimisation. It is worth recalling the reader; as mentioned in the Section-I, the adopted loss minimisation strategy is only an example case selected for depicting optimal VVC. The

number of estimated control actions in each VVC device including the DG units in each hourly period for the regulated system is shown in Table 1. In this paper, the control actions are further investigated using detailed time domain simulation (Simulation Case Study-2).

Figure 6. The derived hourly controller set-points for (a) VRs, and (b) DG1, DG2, and CB1

Figure 7. Variation of (a) active power losses, (b) bus voltages for the unregulated system, (c) bus voltages with optimal VVC, and (d) reactive power imported from the transmission systems in each case

Table 1. Number of estimated VVC actions

Hour	$\sum$ VR Tap Operations	$\sum$ CB Switching Operations	$\sum$ DG Control Actions
00:00 – 01:00 am	17	4	1
01:00 – 02:00 am	7	0	1
02:00 – 03:00 am	9	2	3
03:00 – 04:00 am	2	0	2
04:00 – 05:00 am	2	1	2
05:00 – 06:00 am	2	1	2
06:00 – 07:00 am	4	1	2
07:00 – 08:00 am	0	2	2
08:00 – 09:00 am	4	2	4
09:00 – 10:00 am	4	2	2
10:00 – 11:00 am	4	1	2
11:00 – 12:00 pm	3	0	2
12:00 – 13:00 pm	3	0	2
13:00 – 14:00 pm	2	2	2
14:00 – 15:00 pm	1	0	2
15:00 – 16:00 pm	0	1	2
16:00 – 17:00 pm	2	2	3
17:00 – 18:00 pm	5	0	2
18:00 – 19:00 pm	5	4	2
19:00 – 20:00 pm	2	0	2
20:00 – 21:00 pm	1	4	2
21:00 – 22:00 pm	2	2	2
22:00 – 23:00 pm	6	2	4
23:00 – 24:00 pm	0	1	1

3.2 Simulation Case Study-2

In this section, the distribution feeder system operation under loss minimisation process is tested in time domain

environment using a MATLAB-Simulink model of the system. The main purpose is to observe control actions of tap changing devices under conventional fixed time-graded operation, and the possibilities for tap changing device and DG interactions in steady-state. Hence, only the tap operations are monitored.

A separate MATLAB m-file is used to update the derived controller set-points into the Simulink model. In this case study, load ramping is modeled assuming that the impact of load ramping during a 10-minute (i.e., 600 s) period on the operation of Volt/VAr control devices is quite negligible. The simulated time delays for VR controllers (Type-B type) are 60 s for VR1 and 90 s for VR2. The substation OLTC is simulated with 30 s time delay and 1.03 pu voltage set-value at the secondary of the associated transformer. For OLTC, 16 tap positions (+8/-8) are modeled and magnitude of voltage correction for one tap operation equals to 0.01250 pu (to maintain the voltage within 0.90-1.10 pu). The simulated dead-band of tap changing devices is twice the per unit value of voltage change per tap operation. The total mechanical time delay for substation OLTC, VR1 and VR2 are 5 s, 7 s, and 10 s, respectively. The time delays are not assigned for CB operations and VAr controllers of the DG units, since their time delays are very small compared to the time delays of tap changing devices. The controllers of VRs and CBs are updated simultaneously at the beginning of each hourly control state. The associated VAr controller-responses of DG1 and DG2 are simulated using random sequence with VR and CB controller updates; depicting the instances of DG operations enforced by the requirements of distribution network operator and/or operational limitations associated with the modular DG units and associated controls.

The selected simulation results for conventional operation, where there are significant interactions between DG units and VRs, are presented for different hourly time intervals in Figure 8 (a). These results are derived and presented using individual 10-minute time spans in different hours for clarity purposes. It can be seen that the substation OLTC tap operations have not been altered throughout the simulated daily operation of the test distribution system. It is indicative of the fact that the operation of VRs, the CB and the Volt/VAr support DG units as well as load ramping during 10-minute interval in the simulated distribution feeder system itself do not have any impact on the OLTC target point voltage i.e., substation secondary voltage. Moreover, it can be seen that the load ramping during 10-minute interval has no significant impact on the operation of line VRs thereby violating their dead-band limits. Consequently, it validates the assumption used for simulating the distribution system operation which says impact of load ramping during a 10-minute period on the operation of VVC devices is negligible. These observations are also adopted for designing the proposed strategy for eliminating grid interactions. Furthermore, it is observed that the

variability and availability in DG active and reactive power generations, as simulated, lead to additional and/or counteracting VR tap operations by violating the VR dead-band limits under certain system conditions. This is indicative of the fact that interactions among Volt/VAr support DG units and other voltage control devices can be significant under certain system conditions. It emphasises the requirement of implementing certain control-mechanism for ensuring the coordinated operation among voltage control devices and multiple Volt/VAr support DG units for efficient operation of the distribution system.

The test simulation results shown in the following section reveals that online implementation of controls highlighted under the proposed strategy for eliminating steady-state grid interactions (Section 2.2) is capable of eliminating those interactions among Volt/VAr support DG units and voltage control devices, and thereby avoiding associated conflicting operations and resultant voltage variations in the distribution system. In Figure 8 (a) in each case, the tap operations shown in blue colour are for OLTC, while tap operations shown in green and red colours are of VR1 and VR2, respectively. Also, the voltage profiles shown are for nodes 17 (blue), 32 (red), 42 (green), 64 (light blue), 74 (purple) and 95 (yellow).

3.3 Simulation Case Study-3

In this section, the proposed coordinated operation of voltage control devices and Volt/VAr support DG units incorporating the proposed strategy for eliminating grid interactions is tested using time domain simulation. The distribution system operation simulated in Case study-02 is also considered in this case study, for comparison purposes. The simulation results depicting the instances where tap operations are enacted according to the proposed strategy for eliminating grid interactions are shown in Figure 8 (b). During rest of the 10-minute intervals for each hourly period, no conflicting tap operations are altered and voltage is within the acceptable limits. In summary, it can be seen that the Volt/VAr support from DG and VAr injection from CB, mainly contribute to loss minimisation. Accordingly, the simulation results validate the merits of proposed strategy in eliminating steady-state control-interactions among multiple voltage control devices and Volt/VAr support DG units enacted in a distribution system operation for optimal VVC. For example, during the hour, 17:00–18:00 pm; in Figure 8 (a), the tap operations are altered resulting additional voltage variations mainly due to the interactions caused by DG power injections and control set-point updates. In Figure 8 (b), it can be seen that the associated interactions and conflicting operations are eliminated following the proposed coordinated control strategy highlighted in Section 2.2.

Hour | 2:00 – 3:00 am

(a) Optimal control with conventional time-graded operation

(b) Proposed control with dynamic time-graded operation
Time | 2:00 – 2:10 am

Hour | 8:00 – 9:00 am

(a) Optimal control with conventional time-graded operation

(b) Proposed control with dynamic time-graded operation
Time | 8:20 – 8:30 am

Hour | 9:00 – 10:00 am

(a) Optimal control with conventional time-graded operation

(b) Proposed control with dynamic time-graded operation
Time | 9:00 – 9:10 am

Hour | 11:00 am – 12:00 pm

(a) Optimal control with conventional time-graded operation

(b) Proposed control with dynamic time-graded operation
Time | 11:00 – 11:10 am

Hour | 17:00 – 18:00 pm

(a) Optimal control with conventional time-graded operation

(b) Proposed control with dynamic time-graded operation
Time | 17:00 – 17:10 pm

Hour | 18:00 – 19:00 pm

Figure 8. Simulated VR and OLTC taps under (a) optimal control with conventional fixed time-graded operation, and (b) proposed control with dynamic time-graded (coordinated) operation: selected cases

4. Conclusion

In modern distribution grids, the DG units can be utilised for Volt/VAR support while achieving the desired objectives of the optimal VVC. However, the operation of multiple Volt/VAR support DG units in conjunction with other voltage regulating devices such as OLTC, line VRs and CBs can lead to significant device interactions and possible conflicting operations under certain system conditions. This may be a more complicated phenomenon in the presence of multiple DG units embedded in a distribution system, especially when the DG units are also utilised for system Volt/VAR support. The strategy proposed in this paper provides a versatile approach for deployment of optimal VVC in modern distribution systems with a capability of eliminating possible interactions among the voltage regulating devices and Volt/VAR support DG units by ensuring coordinated operation. Moreover, the proposed strategy can be implemented for unbalanced three phase distribution grids. Application of proposed updated time-graded operation of multiple VVC devices through online event triggered coordination will pave way for successful deployment of optimal VVC in modern distribution grids.

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