Improvement of on-load tap changer performance in voltage regulation of MV distribution systems with DG units using D-STATCOM

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ABSTRACT

This paper presents a new technique for the voltage regulation of a radial medium voltage (MV) distribution grid in presence of distributed generation (DG) units. The proposed technique consists of the coordinated action of on-load tap changer (OLTC) of transformer and reactive power compensation by D-STATCOM. Managing the system voltage using the action of OLTC is one of the most common ways for voltage regulation of MV systems. However, OLTC cannot be used for voltage regulation of long radial distribution feeders as it changes the sending point voltage of the feeder. In this study, the problem of using OLTC for the voltage regulation of a radial distribution feeder will be solved by using reactive power compensation at the DG connected bus. Simulation results reveal that the proposed control method is capable of maintaining the system voltage within the permitted range in the worst scenarios of the test system.

INTRODUCTION

During the recent years, the conventional structure of electrical power systems has been changed by the presence of distributed generation units. Previously, the electric power was generated in large generating stations at a small number of locations (called central generation). In these stations, voltage was stepped up to high voltage (HV) to be transmitted through interconnected HV transmission networks. The voltage was then stepped down to medium voltage and low voltage and distributed through radial distribution networks to the end users. In recent years, there has been a considerable growth in the amount of decentralized generation connected to the distribution systems. As a result, currently, power systems are in a state of transition from conventional systems with unidirectional power flows to active networks with bi-directional power flows. Therefore, new technical challenges have emerged for distribution system operators (DSOs).

Presence of DG units alters the conventional voltage regulation schemes of distribution systems. In the conventional distribution feeder (without DG unit), voltage decreases towards the end of the feeder, as the impedance of line causes a voltage drop. Thus, the biggest voltage drop happens at the end of the feeder based on the amount of load demand. With the presence of DG, if its power exceeds the local demand of load, the power flow direction will be inversed and we must deal with a voltage rise problem at the DG connected bus. Therefore, in the presence of DG units, the voltage violation depends on the amount of load demand as well as on the amount of DG power. When the injected DG power is maximal and the demand of loads is low, the voltage rise may exceed the permitted range.

Traditionally, DSOs have managed their distribution system at the planning stage based on the fit and forget policy using deterministic load flow studies (considering the critical cases) in order to meet the forecast load and to verify protection actions, lines capacity and voltage regulation issues. In presence of DGs, as their output power varies during the day, the uncertainty in distribution system management is increased and the safe operation of the system becomes more complicated. In this situation, implementing an on-line control system based on the active network management policy becomes more crucial.

In recent years, several control strategies have been applied to maintain the voltage of distribution systems within the defined range. Theoretically, different methods can be applied for voltage regulation of distribution systems but the most applicable methods are curtailment of DG power, network reinforcement, OLTC action and reactive power compensation. Since the voltage rise problem is caused by the injected power of DG**,** curtailment of DG active power is one possible method but it does not allow to maximize the benefits of integrating DG units. The voltage profile along the feeder is strictly dependent on the impedance of lines. Therefore, network reinforcement is another possible method but it is expensive, it needs long delays and DSOs normally consider it as the last possible option. Generally, OLTC action and reactive power compensation are the best possible methods but each of these methods has its own advantages and drawbacks which are explained in the following sections. In reference [1], a coordinated voltage control method has been proposed in order to manage the tap changer action of transformer and to control the reactive power of DG units. Also, coordinated control of OLTC and STATCOM based on artificial neural network has been presented in [2].

In this paper, in order to maximize the benefits of OLTC action and D-STATCOM response, a new voltage control method is proposed. The main idea is to concentrate the response of each controller in its most suited working ranges and to consequently use each controller in the defined voltage range which corresponds to its merits.

ON LOAD TAP CHANGER ACTION OF TRANSFORMER

Using OLTC action is the most popular method in voltage regulation of distribution systems because it is easy to implement and design. In this method, the turn ratio of the transformer winding is adjusted by the tap changer mechanism of the transformer when the voltage of the system exceeds the specified range. The tap changer action is normally adjusted by an automatic voltage control (AVC) relay which continuously monitors the system voltage and controls the action of tap changer. The AVC relay works based on the two controlling parameters which are the reference voltage of the regulated point and a defined dead band. This dead band is designed to limit the unnecessary actions of the tap changer. The tap changing operation is normally done with a time delay due to the dynamic response of the OLTC mechanism.

The drawback of the OLTC method is that it cannot be used in voltage regulation of long radial distribution systems because it changes the voltage of the feeder sending point while the biggest voltage violation occurs at the end of line (ending point of the feeder). In this situation, in order to return the ending point voltage inside the permitted range, OLTC must change noticeably the sending point voltage and it can lead to voltage violation at this point of the feeder.

REACTIVE POWER COMPENSATION

Reactive power compensation is a useful method for voltage regulation of distribution systems. Traditionally in distribution systems, capacitor banks have been used to keep the power factor close to 1 and to compensate voltage drop in the heavy load situations. In the DG connected distribution systems, as we must deal with both voltage drop and voltage rise problems, we need a source of reactive power with the ability to work in inductive and capacitive modes. Absorbing reactive power can increase energy losses, decrease the network capacity and influence the loading capacity of the system. Moreover, reactive power compensation is not an effective way for the voltage regulation of distribution systems with a high ratio of R/X.

The needed reactive power of the system can be provided by synchronous machine-based DG units that are able to adjust their output reactive power in order to affect the system voltage. Conventional control systems for reactive power control of synchronous machines are automatic power factor control (APFC) system and automatic voltage regulation (AVR) system. In the automatic power factor control mode, the reactive power of DG (Q_{DG}) follows any variation of the active power of DG (P_{DG}); therefore, the P_{DG}/Q_{DG} ratio is maintained constant in order to keep the system voltage within the limits. However, this method is not an effective way to regulate voltage because it does not consider the load variations of the system.

In the automatic voltage control mode, the difference between the actual bus voltage and a set reference voltage defines the needed reactive power of the system [3]. This action can be explained by a droop characteristic; this droop shows the relationship of the needed reactive power of DG in accordance with the voltage of the system. In reference [4], a dead band for this characteristic (Q_{DG}=f (V)) has been defined in order to limit the exchanged reactive power of DG in the unnecessary range. In reference [5], a new voltage control method has been proposed which combines the advantages of AVR and APFC control systems. It must be noted that the operation of DG units in AVR mode can cause some problems like high field currents, overheating and triggering of over current protection systems. Also, the reactive power compensation is not applicable in asynchronous machine-based DG units like doubly fed induction generator (DFIG). Therefore, dedicating an external source of reactive power can be a better solution. Power electronics based compensators like D-STATCOM (distribution STATCOM) can be used to tackle the current limitations of DGs in reactive power compensation modes.

D-STATCOM

D-STATCOM is a member of FACTS (Flexible AC Transmission System) devices at the distribution level. It is a voltage source converter (VSC) based device which converts a DC input voltage into a balanced set of three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. D-STATCOM can provide a superior solution for voltage regulation, flicker elimination and improvement of power quality. In voltage regulation mode, it controls the voltage of the regulated point by adapting the amount of injected or absorbed reactive power. As long as the exchanged reactive power stays within the maximal and minimal limits, the voltage is regulated at the target voltage value. Figure 1 shows a typical V-I characteristic of D-STATCOM.

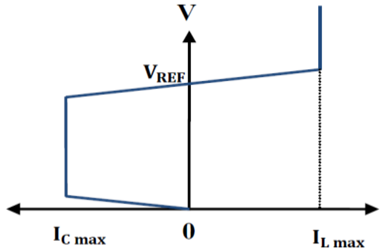

Figure 1: Typical V-I characteristic of D-STATCOM

As it can be seen, if the voltage of the system is lower than the reference voltage (V_{REF}), STATCOM works in capacitive mode and if it is higher than V_{REF}, STATCOM works in inductive mode.

PROPOSED VOLTAGE CONTROL METHOD

In this study, the drawback of using OLTC in voltage regulation of a radial distribution feeder with DG unit at the end of the line is solved by using reactive power compensation (offered by D-STATCOM) at the DG connected bus. In order to implement this method, different working ranges are defined for the action of the above-mentioned voltage control methods.

Generally, the safe operation of the network is defined by the permitted voltage limits. In this paper, the permitted range of voltage is equal to ± 3% of the reference voltage (100%). Therefore, if the voltage of the regulated point is within these limits (103% and 97% for the maximum and minimum permitted values, respectively), no corrective action of the controller is needed. In the radial distribution feeder with DG unit at the end of the line, the biggest voltage violation happens at the end of the line. Thus, in this study, the DG connected bus is chosen as the regulated point in order to ensure the voltage of all buses is within the safe range. OLTC in conjunction with AVC relay receives the ending point voltage of the feeder and regulates the voltage towards the feeder. However, as the OLTC action changes the sending point voltage of the feeder to keep the ending point voltage within the permitted limits, the action of OLTC can only manage the voltage violations lower than ± 3% (the permitted range) of the reference voltage. Clearly, if the action of OLTC is allowed to manage the voltage variations of more than ± 3%, the sending point voltage will be violated from the tolerated range. In this paper, in order to ensure the safe operation of OLTC action, its action has been limited and it can manage the voltage violations lower than ± 2.5% from both permitted values (103% and 97%). This is an optimal range in order to limit the frequent use of D-STATCOM (as it can lead to the increase of the system losses). Also, 0.5% margin is considered for the impact of reactive power compensation (at the end of the line) on the sending point voltage of the feeder. Figure 2 shows the working ranges of OLTC action.

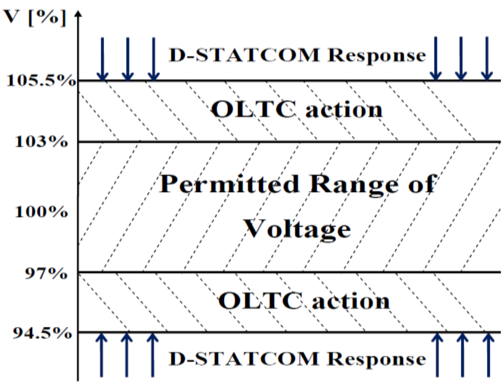

Figure 2: Working ranges of each controller in the proposed voltage regulation scheme at the regulated point

The dead band of OLTC action is considered equal to the permitted range of voltage (± 3%). Thus, if the voltage of the DG connected bus is within the permitted range, OLTC will not act. When the voltage of the regulated point exceeds the permitted range, with the forced (since it is not actually the normal limitation of the OLTC mechanism) limitation of the OLTC (± 2.5%), it changes the sending point voltage in order to adjust the ending point voltage of the feeder.

As it can be seen in figure 2, when the voltage violation is outside of the range that has been defined for OLTC action, reactive power compensation by D-STATCOM is used to return the voltage of DG connected bus inside the range that is acceptable for OLTC action. In other words, D-STATCOM is only used when OLTC action reaches its limits (105.5 and 94.5 for its upper and lower limits, respectively) and OLTC cannot work anymore. In this situation, the OLTC action manages ± 2.5% of the voltage violation and the rest of the voltage violation is compensated by D-STATCOM. Therefore, in the extreme voltage violation conditions, D-STATCOM with its fast response instantly brings back the voltage to the upper or lower limit of the OLTC action (105.5 and 94.5, respectively). In this way, thanks to the action of D-STATCOM, the voltage violation will be within the defined range of OLTC action and OLTC can effectively manage the voltage problem (see figure 2).

Figure 3 shows the proposed V-I characteristic of D-STATCOM. The defined dead band enables us to limit the D-STATCOM action in the unnecessary situations and only use it in the extreme voltage violations.

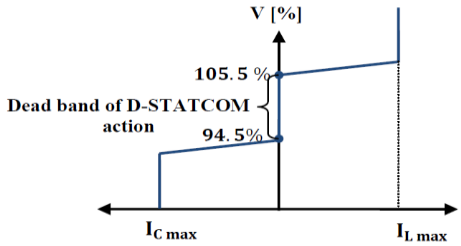

Figure 3: Proposed V-I characteristic of D-STATCOM

SIMULATION RESULTS

In order to validate the proposed voltage regulation scheme, a radial distribution system is considered which is shown in figure 4. The system under study consists of a DG unit which is located at the end of the feeder where D-STATCOM is also installed. The OLTC mechanism is installed on the secondary side of the HV/MV transformer (70/11 KV).

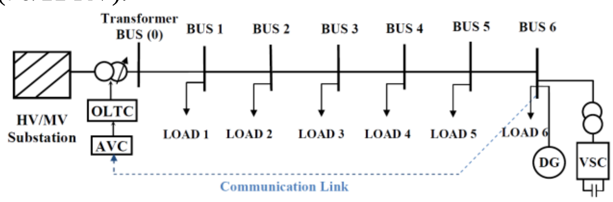

Figure 4: The investigated system

The parameters of the investigated system are as follow:

- Impedance of the each section of the distribution feeder = 0.4 + j 0.35 Ω
- Nominal value of each load = 0.8 MW (with the lagging power factor equals to 0.9)
- Maximum power of DG unit (P_{DG})= 5.5 MW

In this paper, the worst cases in the voltage regulation of the investigated system are simulated. The simulations are carried out by using NEPLAN. The first test case (worst case 1) is when DG generates its maximum power and the demand of the load is minimal (10% of the nominal load). Figure 5 shows the profile of the voltage along the feeder in this situation.

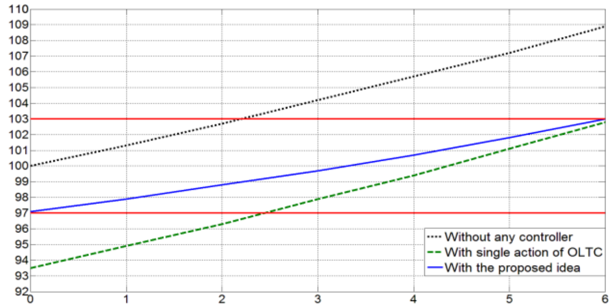

Figure 5: Voltage profile of the system buses in the worst case 1

As the voltage rise at bus 6 is more than the permitted range of the voltage (± 3%), the single action of OLTC cannot manage the voltage rise along the feeder. The single action of the OLTC leads to a voltage drop at the sending point of the feeder (93.5% at bus 0). Figure 5 shows that the proposed idea is capable of managing the extreme voltage rise at bus 6. As it can be seen, without any controller, the voltage rise at bus 6 is about 6% and based on the proposed idea, 2.5% of this voltage rise was managed by OLTC action and the rest of the voltage rise (3.5%) was compensated by D-STATCOM response. In this case, the absorbed reactive power of D-STATCOM is 1.85 Mvar (inductive mode). The second worst case (worst case 2) is considered when the injected power of DG is minimal (P_{DG}= 0) and the demand of the load is maximal (100% of the nominal load). Figure 6 shows the profile of the voltage along the feeder in this situation.

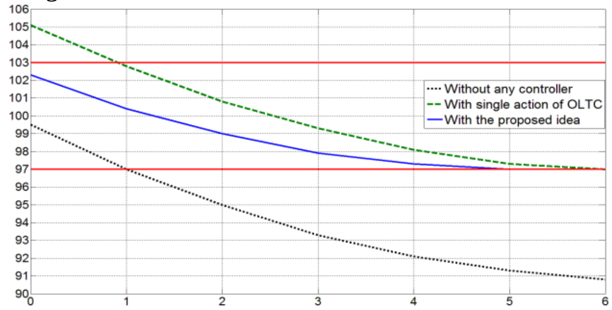

Figure 6: Voltage profile of the system buses in the worst case 2

Like the previous case, the single action of OLTC cannot effectively manage the voltage drop at bus 6 (more than 6%) while the proposed idea with the combination of OLTC action and D-STATCOM response is able to keep the voltage of all buses within the predefined limits. In this case, the reactive power of D-STATCOM is equal to -1.75 Mvar (capacitive mode).

Based on the simulation results, it can be concluded that the proposed method is able to keep the voltage of the all buses within the limits. However, it must be noted that the exchanged reactive power of D-STATCOM can lead to the increase of energy losses. Table 1 presents the evaluation of system losses in the studied cases. It can be noticed that the operation of D-STATCOM in the inductive mode increases the energy losses of the system.

Table 1: Energy losses of the system

Test case	P_{DG}	P_{loads}	$Q_{DSTATCOM}$ (Mvar)	P_{loss} (MW)	Q_{loss} (Mvar)
worst case 1 (without controller)	Max.	Min.	0	0.456	0.399
worst case 1 (proposed controller)	Max.	Min.	1.85	0.585	0.512
worst case 2 (without controller)	Min.	Max.	0	0.28	0.245
worst case 2 (proposed controller)	Min.	Max.	-1.75	0.217	0.19

CONCLUSION

In this paper, a new idea for the voltage regulation of radial distribution systems with DG unit at the end of the line was presented. The proposed idea was based on the combination of two different control methods which are OLTC action and reactive power compensation. The idea was to use the OLTC action in the predefined range (based on the permitted range of voltage) and allow D-STATCOM to manage the rest of the voltage violations. Simulation results revealed that the proposed method enables us to efficiently manage the voltage control problem of a radial MV distribution system in the worst working conditions. Moreover, as the D-STATCOM is only used in the extreme voltage conditions (when OLTC cannot work anymore), it does not considerably increase network losses. In future research, a practical evaluation and the cost of implementation of the proposed method will be investigated.

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