DMS – BASIS FOR INCREASING OF GREEN DISTRIBUTED GENERATION PENETRATION IN DISTRIBUTION NETWORKS

by

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Modern (electric power) distribution utilities are faced with high penetration of distributed (electric) generation. Renewable generation is of prime interest. Within this generation, the green one incorporating solar (photovoltaic) and wind generation is the most important. Consequently, the following two imperatives are established in modern distribution utilities: (1) absorption of as much of available (connected to network) green generation as possible and (2) increasing of the limit of green distributed generation penetration. This generation is a significant basis of Smart Distribution Grid Concept. Distributed generation transfers passive distribution network into active one. The active distribution network analysis, control, operation management and planning become significantly complex. This complexity radically hinders the achievement of two above stated imperatives referring to the distributed generation penetration. This paper proves that Distribution Management System is a unique powerful system that integrates all tools necessary for surpassing main difficulties in the achievement of the both imperatives. The proof is obtained by the elaboration of a set of power applications (mathematical calculations) integrated in the Distribution Management System. The most important power applications, which deal with voltage/reactive power control, are specially stressed.

Key words: *distribution network, green distributed generation, distribution management system, smart grid*

Introduction

Modern (electric power) distribution utilities are faced with high penetration of distributed (electric) generators (DG). The most attractive are those which use renewable and green – solar (photovoltaic – PV) and wind energy (green distributed generators – GDG). This penetration is strongly forced by modern societies (green energy acts) as a part of the smart distribution grid (SDG) concept. The capacity of GDG spreads out from small (dispersed) solar and wind generators connected to low voltage (LV) network (micro GDG which are fed in tariff usually by the state – MicroFIT), GDG with a few MW ratings connected to medium voltage (MV) network, up to GDG farms connected to (sub)transmission network. GDG connected to distribution (LV and MV) network are considered in this paper.

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The penetration of DG in distribution networks changes the network nature from passive to active. Analysis, control, operation management and planning of an active distribution network become significantly complex. Independently of this complexity, the following two *imperatives* referring to GDG penetration are established in modern distribution utilities:

(a) *Absorption of the GDG production* – absorption of as much of the available (connected to network) GDG production as possible,

(b) *Increasing of the GDG penetration limit* – increasing of the limit of new GDG integration into distribution networks to the maximal extent.

The higher the DG penetration is, the higher the level of DG influence on network operation is. The network voltage profiles rise (over the upper network voltage limits) is the most expressed influence of DG on distribution network operation. A great number of papers deal with this issue [1-6]. In addition, DG influence short-circuit currents levels [4, 7]. This further influences breakers/fuses capacities and relay protection setting and coordination, as well as network relay protection concept. Mutual interference between DG penetration level and network (re)configuration, losses, harmonics and Combined Heat and (electric) Power (CHP) facilities operation are discussed in [8-12], respectively. Service restoration after isolation of faulted part(s) of distribution network, in the presence of DG, is considered in [13-15]. Planning aspect (optimal allocation) of DG is considered in [4, 10].

The referenced papers do not exhaust all aspects of influence of DG penetration on distribution networks operation. But, they are sufficient to prove that the achievement of both above stated modern distribution utilities‘ imperatives is a very complex issue. Consequently, it is necessary to apply complex tools for dealing with this issue. The most complex DG are GDG due to their intermittent production. Thus, their importance and complexity are main motivation to emphasize them in this paper. The human experience and ad-hock rules (rules of thumb) are abandoned as tools for dealing with the issue of GDG penetration in distribution networks long ago [16]. Single line voltage drop compensation (SLVDC), which is provided by under load tap changing supply transformers (ULTCT) and voltage regulators (VR), as well as reactive power (var) resources [1, 17, 18], are not sufficient for dealing with this very complex issue. DG production curtailment [2] is a tool that is contradictory to the first imperative referred to GDG penetration. As said above, the complexity of this issue is a consequence of the fact that GDG do not influence only voltage profiles of distribution networks. Their influence on short-circuit current levels, breakers/fuses capacities, relay protection setting and coordination, relay protection concept, optimal network configuration, losses, harmonics, CHP facilities operation, service restoration, network operation and development planning are also very significant aspects of GDG penetration. The complexity of the considered issue rises with the increase of the level of GDG penetration. The chapter *Levels of GDG penetration* defines seven levels of this penetration. These levels are in direct relation with the complexity of tools which are necessary to be applied for dealing with GDG. A huge number of computer tools for dealing with this issue are listed and discussed in [19]. These tools are more or less stand alone. Instead of applications of such a large numbers of stand alone tools, this paper proves that distribution management system (DMS) is a unique powerful system for surpassing main difficulties in the achievement of both above stated imperatives referring to GDG penetration. Practically all tools necessary for dealing with GDG penetration are integrated into DMS. Main DMS power applications (mathematical calculations), which are necessary for dealing with GDG penetration, are described in chapter *DMS power applications*. An application of DMS for dealing with GDG penetration in distribution networks is described in chapter *Application of DMS*. Due to lack of space in the paper, only the utilization of DMS Volt Control power application is specially stressed. It is shown that ULTCT and VR can be very effectively managed by DMS for the purpose of achievement of both imperatives referring to GDG penetration. Networks with uniform and networks with non-uniform distribution of GDG are considered. In addition, the idea of the procedure aimed at selection of locations and sizes of VR (network planning issue) for the purpose of realization of both stated imperatives is presented here. Chapter *Steps of DMS power applications introduction* lists a set of successive steps of introduction of DMS power applications in a distribution utility. These steps are fully consistent with the rise of the GDG penetration level. The Conclusion and References are presented in chapters *Conclusions* and *References*. Coordinated operation of ULTCT (supply transformers) and VR installed in depths of feeders (supplied by ULTCT) is presented in the *Appendix*.

Levels of GDG penetration

The operation of GDG is intermittent. Figure 1 presents typical production profiles (GDG production models) of a PV DG for three different profiles of daily insolation. Wind GDG production models are similar, but they are protracted over all 24 hours of the day. This intermittency influences network equipment functionality. The higher the GDG penetration is, the more influenced network equipment functionality is. In accordance with this influence, GDG penetration can be classified as shown in tab. 1.

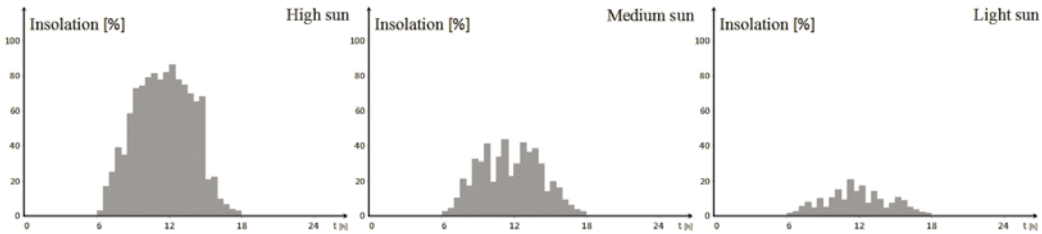

Figure 1. Typical productions of a PV DG for three different profiles of daily insolation

With a small number of exceptions, GDG with higher ratings are usually three-phase and they are usually connected to MV network through corresponding transformers; GDG with smaller ratings (*e. g.* MicroFIT) are usually single-phase and they are usually connected directly to LV network – fig. 2.

To absorb as much of the available generation as possible and, consequently, to increase the GDG penetration limit, different tools (procedures) for network management and planning of its development have to be applied. All these tools are integrated into the DMS.

DMS power applications

The DMS is the basic platform of the modern SDG concept. It is applied for distribution network management and development planning in an optimal way from the point of view of a wide range of criteria. Basically, the DMS integrates real-time supervisory, control and data acquisition (SCADA) system, Network Data Base and Network Mathematical Model, as well as a set of power applications (mathematical calculations) [20]. DMS power applications which are the most important for the considered matter, together with a brief description of their functionality, are listed below. They are directly used for realizing both imperatives referring to GDG penetration stated in the Introduction.

(1) *Power flow* – This is the first basic DMS power application. It is aimed at calculation of network state, for specified network root voltage, loads and GDG production.

Table 1. Levels of GDG penetration

Level No.	Influence on:	Comment
1	No influence	The number and ratings of GDG is so small that they do not influence network equipment functionality.
2	Circuit breakers/fuses capacities	It is necessary to increase circuit breakers/fuses capacities.
3	Volt/Var control devices setting	It is necessary to reset automatic voltage regulators (AVR) and controllers of Volt/Var control equipment (ULTCT, VR and Var resources).
4	Relay protection setting and coordination	It is necessary to reset and recoordinate relay protection.
5	Relay protection concept	It is necessary to change the concept of relay protection due to the appearance of reversal power flow.
6	Network reconfiguration	The presence of DG radically changes the optimization criteria and algorithms for providing optimal network configuration.
7	Network reconstruction – (re)installation of new equipment	It is performed when other measures cannot keep network state within technical limits (voltage, currents, harmonics levels, *etc.*).

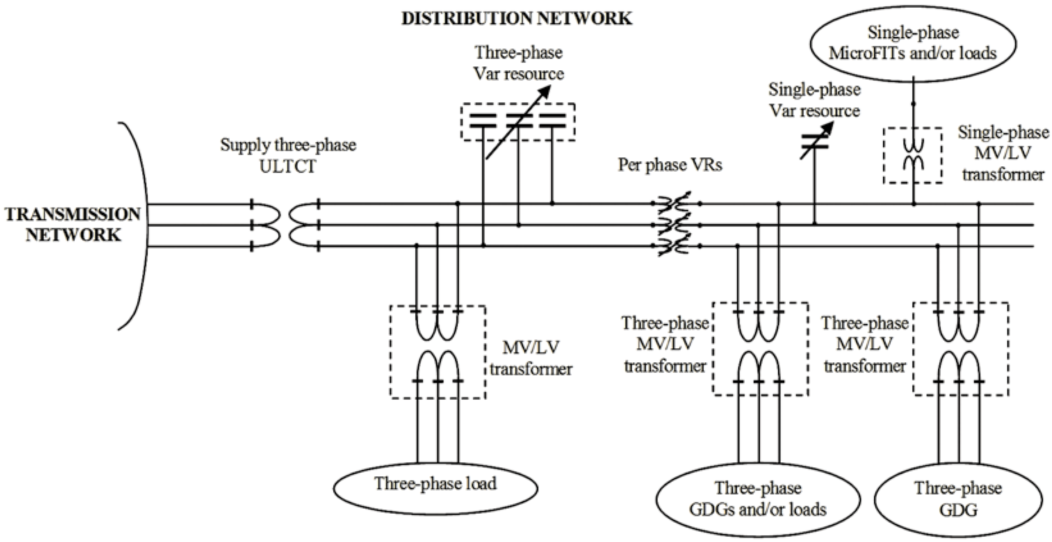

Figure 2. Distribution network with different ratings of DG and different connections of DG to the network

(2) *State estimation* – This DMS power application is mainly used in real-time condition for the assessment of current network state in the presence of GDG. The basic data for the function execution are state variables, switchgear statuses and tap changers positions of ULTCT and VR, as well as statuses of controllers of var resources monitored by SCADA system, historical data about the consumption, as well as monitored GDG production or production estimated on the basis of data provided by the weather information system. In addition, state estimation power application is used in study mode for providing data for volt/var control devices setting. It integrates the power flow power application as its main part.

(3) *Fault calculation* – It is the second basic DMS power application used for the calculation of network state in fault condition (short-circuit and phase breaking), in the presence of GDG.

(4) *Circuit breakers/fuses capacity* – This DMS power application is aimed at checking of breakers and fuses capacities against network short-circuit currents, in the presence of GDG. (These currents are calculated by execution of the fault calculation power application.)
(5) *Relay protection* – This DMS power application is used in two modes: 1) for (re)setting and (re)coordination of relay protection caused by DG operation and 2) for the selection of a new protection concept necessary in distribution networks with reversal power flows caused by GDG operation (*e. g.* introducing the distance protection).
(6) *Volt control* – This DMS power application is mainly aimed at real-time managing of remotely controlled ULTCT and VR, as well as at setting of their AVR, taking into account GDG operation. In addition, the power application is used for setting of no load tap changing transformers, at seasonal level.
(7) *Var control* – This DMS power application is mainly aimed at real-time managing of remotely controlled capacitor banks (CB), as well as at setting of their controllers, taking into account GDG operation. In addition, the power application is used for setting of no load tap changing CBs, at seasonal level.
(8) *Volt/Var control* – This DMS power application represents a coordinated execution of the Volt Control and Var Control power applications. It is used for the optimization of network state in accordance with a specified criterion. Turning back network state within the technical limits, network voltage profile and reactive power flows criteria are of prime interest for the matter considered in this paper. The basic resources for this optimization are voltage Volt/Var control resources. Different levels of GDG operation are taken into account.
(9) *Network reconfiguration* – This DMS power application is used for the optimization of network topology, according to specified criterion. The elimination of technical limits violations (high voltages caused by GDG operation) criterion is of prime interest for the considered matter.
(10) *Supply restoration* – In passive distribution networks (without DG), this DMS power application is used for providing supply of deenergized parts of a network occurred after faulted elements isolation. In such networks, the reserve supply of deenergized parts is provided by adjacent energized network‘s parts. Thus, islanding of a network is not possible. In active networks (with DG), supply restoration power application takes into account the presence of DG. Islanding of a network is possible in situations when the islands are supplied by synchronous DG combined with GDG (GDG are not usually provided by speed governors and voltage regulators).
(11) *Harmonic analysis* – This DMS power application is used for analysis (calculation) of harmonics caused by different sources, including GDG, as well as for suggestion of measures to reduce the harmonics to allowed levels.
(12) *Switching sequence management* – This DMS power application is used for both derivation and in-field performing of a set of switching operations which are necessary to transfer a network from current to target topology (*e. g.* to transfer a part of a feeder with GDG to an adjacent feeder, for execution of supply restoration process, *etc.*). The most part of the switching operations are performed remotely using SCADA system.
(13) *Optimal network reinforcement* – This DMS power application is used for solving local network problems caused by GDG operation. The results of its execution consist of suggestions for (re)installation of small devices with local effects. For instance, the replacement of services transformers without taps with ones provided with taps (no load tap changing transformers), installation of voltage boosters, the replacement of lines conductors with ones of larger cross-section *etc.*

(14) *Volt/Var devices planning* – This DMS optimization power application is used for optimal planning of new Volt/Var control resources (ULTCT, VR, CB) in accordance with a specified criterion [*e. g.* network voltage profile, losses, reactive power taken on from (sub)transmission network, *etc.*]. One of the main optimization constraints is specified GDG penetration level.

(15) *Network development planning* – This DMS power application is used for optimal medium- and long-term network development planning. The optimization constraint that is of prime interest for the matter considered in this paper says: a network of a specified supply transformer (supply substation) has to be designed to provide penetration of a specified quantity of GDG of a specified type (*e. g.* solar and/or wind).

Application of DMS

Following two imperatives referring to DG penetration, which are established in modern distribution utilities, are stated in the Introduction: (1) absorption of the GDG production and (2) increasing of the GDG penetration limit. Seven levels of influence of GDG penetration in network operation are stated in chapter *Levels of GDG penetration*: (1) no influence and six levels with the influence (2) circuit breakers/fuses capacities, (3) Volt/Var control devices setting, (4) relay protection setting and coordination, (5) relay protection concept change, (6) network reconfiguration and (7) network reconstruction.

DMS power applications are used to realize both imperatives, as well as to fit network operation within technical limits in networks with any level of GDG penetration. The technical limits consist of upper and lower bus voltages limits, conductors‘ upper current limits, harmonics levels *etc.* Two types of networks with different GDG distribution will be considered in this section: (1) networks with uniform GDG distribution and (2) networks with non-uniform GDG distribution. The basic voltage control resources – ULTCT and VR, applied for fitting network state within technical voltage limits, as well as corresponding DMS power applications, are considered in the following text. This is done only as an example of DMS usage for the purpose of achievement of both imperatives referring to DG penetration.

Uniform GDG distribution

The easiest case of managing the operation of a distribution network containing GDG is when they are uniformly distributed throughout the network. For such a network, only two *ultimate network conditions* have to be analyzed: (1) GDG do not produce electric energy in heavy load condition – *no sun (wind)/heavy load* condition and (2) GDG produce high electric energy in light load network condition – *high sun (wind)/light load* condition. When DG are uniformly distributed throughout the network, if the network states in both ultimate conditions are within the technical limits, the same will be provided in all other conditions which are “between” the ultimate ones. Thus, only the two network ultimate conditions have to be elaborated using the volt control DMS power application listed in the chapter *DMS power application*. The main result of this elaboration consists of setting the AVR of voltage control devices to keep the network states within technical limits in both conditions. Thus, a room for providing additional optimization criteria is increased. These criteria could be: (1) operation security, (2) “best” voltage profiles, (3) reactive power taken on from (sub)transmission network, (4) losses, *etc.* They can be achieved by execution of the DMS power applications listed in the chapter *DMS power applications*.

Instead of setting the AVR of voltage control devices to keep the network states within technical limits, the volt control power application can be executed for derivation of commands for optimal moving of tap changers of voltage control devices in real-time condition. The AVR of voltage control devices are bypassed in these cases, and the derived optimal commands are directly executed by SCADA system.

Non-uniform GDG distribution

Similar loads are ones with the same scaled daily load profiles (DLP) [21]. For instance, the loads of two service transformers are similar if DLP of one service transformer can be derived from the DLP of the other service transformer by multiplication of the second one with a constant. When the loads of service transformers of the network belonging to a supply transformer area are mutually similar, in the most number of cases a ULTCT (supply transformer – the single network source) is sufficient for providing voltage control in its network with sufficient quality. In the case when the DLP of feeder heads are not similar (the scaled DLP of feeder‘s heads differ one from the other), the ULTCT would not provide satisfactory voltage profiles in the entire supply transformer network. The smaller the similarity of these loads is, the lesser the quality of feeders‘ voltage profiles is. The loads similarity is significantly degraded by GDG operation. A better solution consists of VR installed at each feeder head instead of the ULTCT. In this case, the supply transformer can be off-load tap changing one, or a transformer without taps. In the case when loads along a single feeder are not similar, additional VR have to be installed along the feeder. The VR might be accompanied by corresponding var resources.

This control is significantly more complex than one in the previous – uniform distribution of GDG. The Volt Control DMS power application listed in the chapter *DMS power applications* is executed in this case also. The main result of this execution consists of coordination of ULTCT and VR controls for the purpose of keeping the network states within technical limits. Like in the previous case, this control can be performed by setting the AVR of voltage control devices (ULTCT and VR) or by issuing commands for optimal moving of tap changers of these devices in real-time condition.

Voltage control by ULTCT and VR

High penetration of GDG implies significant change in DLP. Thus, when GDG are not uniformly distributed in a network of a supply transformer, the loads fed by the transformer are not similar. Let us consider a MV feeder presented in fig. 3. It is fed by an ULTCT. The feeder supplies several single- or three-phase service (MV/LV) transformers. Each one supplies its own LV network. Only LV network of one transformer is stressed. This network supplies LV loads in the presence of GDG (*e. g.* MicroFIT). Point A of the feeder is the border between the first feeder part containing a significant quantity of GDG, and the second part that does not contain GDG. These GDG radically change the load profile of the first part of the feeder regarding the load profile of the second part.

In high sun/heavy load condition, the first part of the feeder does not require increasing of the ULTCT secondary side voltage to prevent the violation of lower voltage limits in its LV networks with a large quantity of GDG’ production. At the same time, the second part of the feeder requires increasing of the voltages to prevent the violation of lower voltage limits in its heavy loaded LV networks. These two requirements are contradictory for a single ULTCT. To cope with this situation, a certain number of GDG must be disconnected from the network. This is contradictory to the first of two imperatives referring to GDG penetration. Instead of this, a VR can be installed in point A (fig. 3). This VR will decouple steady-state effects of voltage control of the first part (performed by ULTCT) from the voltage control of the second part of the feeder (performed independently by the VR).

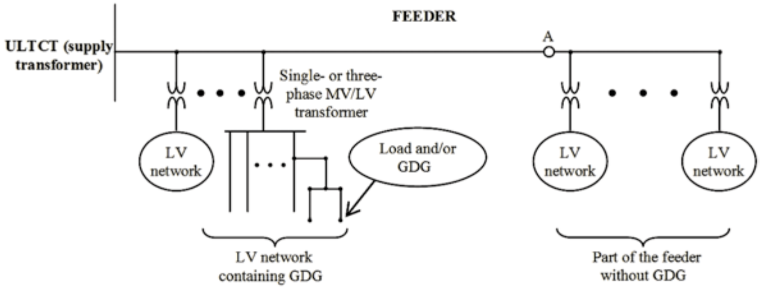

Figure 3. Considered feeder

This consideration presents the idea of the procedure aimed at selection of locations and sizes of VR for the purpose of realizing both stated imperatives referring to GDG penetration (network planning issue).

Let us consider a VR provided by an AVR – fig. 4(a) (*e. g.* the VR installed in point A in fig. 3). The VR secondary side voltage U and current I are AVR inputs. AVR output consists of a signal for moving of the VR‘s tap changer up/down for a single position. Three usual types of AVR‘s voltage control laws are presented in fig. 4(b). Any voltage control law consists of a line. This line shows how high the secondary side voltage of VR for the actual value of its secondary side current will be, *e. g.* point B in fig. 4(b) (line 3). The coordinates of this point are (I_B, U_B). They mean: if the VR secondary side current equals I_B, the AVR would sent signals periodically for moving the VR tap changer, until the secondary side voltage of VR will achieve value U_B, independently of the voltage of the VR primary side. From the set of parameters of VR‘s AVR (voltage set point, dead zone, time delay, control limits *etc.*), only the *voltage set point* U_{max} and *time delay* T_d are of interest for the paper. Voltage set point is presented in fig. 4b. Time delay T_d is the time (in the range of 10 to 60 seconds generally) between the initiation of control action and sending the AVR signal toward the driver of the transformer tap changer to move it for a single position up/down. All these AVR‘s parameters are calculated by application of the DMS and might be set remotely by SCADA system. For a certain network, with known load, the voltage control laws fig. 4(a) are selected by execution of the volt control power application [22, 23].

The most frequently used voltage control law of VR (and ULTCT) is the straight line 1 presented in fig. 4(b). The value U_{max} was defined above as the VR (ULTCT) voltage set point. The current I_{max} represents the secondary side VR (ULTCT) maximal expected current. This

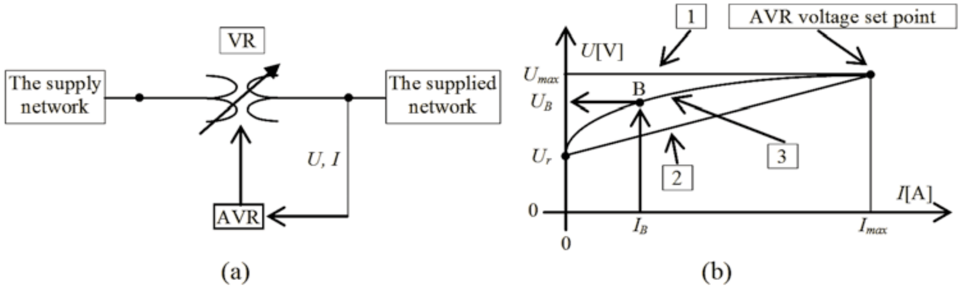

Figure 4. AVR of ULTCT or VR and its voltage control law

voltage control law is termed *constant set point voltage control law*. This means that VR will provide the same voltage U_{max} independently of the VR load (the load supplied by the VR). In other words, the same voltage U_{max} will be provided for both the light and high load conditions of the network. This is generally the main drawback of this type of voltage control law. It is especially inconvenient for networks with high quantity of GDG. Let us consider the two already considered ultimate network conditions: (1) In high sun (wind)/light load condition it is necessary to decrease the voltage of the supplied network (containing high quantity of GDG which produce high power); (2) In no sun (wind)/heavy load condition it is necessary to increase the voltage of the supplied network (independently of the high amount of GDG which do not produce power). Therefore, the VR's voltage set point U_{max} must be decreased to prevent violation of upper voltage limits in LV network in the high sun (wind)/light load conditions. Thus, by application of the described constant set point voltage control laws (the secondary VR side voltage is constant, independently of network state), the voltage quality in the network during a considered time period is more or less degraded.

The voltage control law of type 2, fig. 4(b), is generally more convenient, especially for networks with high amount of GDG. This type of voltage control law is termed SLVDC above. Generally, this voltage control means: (1) In no load condition of the network ($I = 0$), the voltage provided in the VR secondary side equals the network rated voltage U_r; (2) In high load condition of the network (the VR load equals its rated load), the voltage provided in the VR secondary side equals the voltage set point U_{max} (higher value than U_r). It is obvious that such a voltage control law spontaneously decreases the voltages of VR secondary side when the GDG increase their production (the VR secondary side load decrease). Reference [1] proves that the use of the volt control power application, which takes into account VR (and ULTCT) provided with SLVDC, significantly increases both the absorption of the GDG available production and their penetration limit. In some distribution utilities, one can find AVR with voltage control laws of type 3, fig. 4(b). Their properties, from the point of view of the considered matter, are similar to the SLVDC.

The DMS volt control power application can be used in two ways to deal with coordination of ULTCT and VR: (1) In real-time mode, all remotely controlled ULTCT and VR can be managed in closed loop to continuously provide the maximal absorption of GDG available power; (2) Periodically, in operation planning mode, the volt control power application is used for calculation of optimal voltage control laws of ULTCT and VR to provide the maximal absorption of GDG available power in a specified period.

The idea for providing such a voltage control is presented in fig. 5. A part of the network that contains a certain amount of GDG is considered. This part is supplied by a VR (or ULTCT) provided by AVR. The DLP of all loads and rated powers of all GDG are known. A day with a certain DLP is considered. The abscissas *t* [h] of the diagrams in fig. 5 represent the time of the day; the ordinates *U* [V] represent the secondary side voltages of VR. They are provided by operation of its AVR. The voltages are scaled at the LV level (*e. g.* 120 V in North America). The curves marked by *Upper limit* and *Lower limit* determine the allowed zone which the VR's secondary side voltage must belong to. They are calculated with the volt control power application. If the VR's voltage set point belongs to the presented allowed zones during the day, the voltage of not one network bus would violate the stated technical limits. Figure 5(a) presents the case with annulled GDG production [no sun (wind) condition]. Figure 5(b) presents the case with rated GDG production [high sun (wind) condition]. The zone in fig. 5(c) is derived from previous two figures by using the lower limit from the first case and the upper limit from the second case. This zone means: if the VR voltage set point belongs to this zone during the day, the voltages in the considered network will not violate the specified voltage limits, independently of the GDG production.

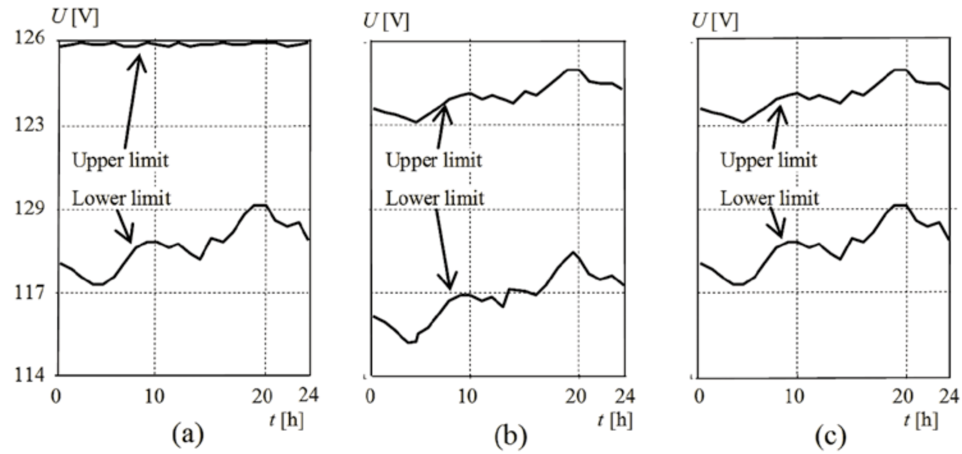

Figure 5. Allowed zones for ULTCT's or VR's voltage set point: (a) zero production of GDG, (b) rated production of GDG, (c) independent of production of GDG

Co-ordinated operation of ULTCT (supply transformer) and VR installed in the depth of a feeder (supplied by the ULTCT) is presented in the *Appendix*.

Steps of DMS power applications introduction

Chapter *DMS power applications* briefly described the main DMS power applications and their usage for achievement of both imperatives referring to GDG penetration: (1) absorption of the GDG production and (2) increasing of the GDG penetration limit. The chapter *Application of DMS* specially stressed the application of ULTCT and VR (main voltage control resources) for the same purpose. This chapter proposes the steps of introduction of the described DMS power applications in distribution utilities practice. They are ranked in accordance with levels of GDG penetration (tab. 1) and their cost (new equipment installation). In addition, the consideration given in the following text offers types of analyses, management or reconstruction of a network, which have to be performed before issuance of a license for connection of a single or a few GDG simultaneously to a network.

Step 1 – Power flow and *state estimation*: Continual execution of these power applications confirms that the installed GDG do not influence normal network operation. Also, the results of their execution signify the situation when increased amount of GDG causes voltages which violate specified voltage limits.

Step 2 – Volt control: This power application is used as the first tool for elimination of network voltage limits violations, caused by GDG operation (Appendix).

Step 3 – Var control, *volt/var control* and *switching sequence management*: In addition to volt control, var control and volt/var control power applications are aimed at optimization of network state, in the presence of GDG, taking into account voltage limits. Switching sequence management power application is aimed at both determining and performing of the list of switching operations necessary to transfer a network from current to target network state (*e. g.* by changing tap positions of ULTCT and VR). A part of the listed switching operations can be performed by SCADA system. The other operations (which are not remotely controlled) must be performed manually.

Step 4 – Network reconfiguration: This power application is aimed at MV and LV networks reconfiguration in presence of GDG. As noted above, the presence of DG radically changes the optimization criteria and algorithms for providing optimal network configuration. Previously described switching sequence management power application is used for derivation and performing of the list of switching operations necessary to transfer a network from current to target topology (*e. g.* to transfer a part of a feeder with GDG to an adjacent feeder). The part of these switching operations (which are not remotely controlled) must be performed manually.

Step 5(a) – Fault calculation and *relay protection* (first mode): Both power applications are used for calculation of short-circuit current levels and resetting/recoordination of the existing relay protection to adapt it to network operation in the presence of GDG.

Step 5(b) – Fault calculation and *relay protection* (second mode): The power applications are used for change of relay protection concept, from the concept aimed at networks without reversal power flows to protection adapted to networks with reversal power flows (*e. g.* introducing of distance protection).

Step 6 – Breakers/fuses capacity: In addition to already introduced fault calculation, this power application is used for checking the capacities of breakers and fuses in a network with increased amount of GDG. The results of this power application signify the necessity for replacement of the existing breakers and fuses with new ones with higher capacities.

Step 7 – Supply restoration: The power application is used for providing supply of network parts which were deenergized after fault isolation. It takes into account the available GDG and possible islanding of a network.

Step 8 – Harmonic analysis: The power application is used for harmonics analysis caused by GDG operation and suggestion of measures to reduce the harmonics to allowed levels.

Step 9 – Optimal network reinforcement, *volt/var devices planning* and *network development planning*: The power applications are used when other tools cannot maintain network state within technical limits in the case of high level of GDG penetration. The results of these power applications executions consist of recommendations on how a distribution network has to be reconstructed to realize both imperatives referring to GDG penetration.

Networks of distribution utilities differ between them in the capacity of their power equipment, SCADA system quality (amount of monitored and controlled network points), DMS quality (amount of integrated DMS power applications), relay protection level and concept, volt/var control resources and the level of their automation (*e. g.* AVR with constant voltage set point or provided with SLVDC), *etc.* Therefore, the application of any of the described steps will give different effects for different distribution networks. To get insight into the efficiency of the application of these steps for a certain distribution network, it is necessary to perform a study containing simulations of application of all described steps.

Conclusions

The experience in the operation of modern distribution networks shows that ad-hock rules (the rules of thumb) and voltage/reactive power control by application of ULTCT, VR and var resources are not sufficient to achieve both imperatives of modern distribution utilities regarding the penetration of green energy in their networks: (1) absorption of the GDG production and (2) increasing of the GDG penetration limit. This is the consequence of the fact that GDG do not influence only voltage profiles of distribution networks. Their influence on circuit breakers/fuses capacities, relay protection setting and coordination, relay protection concept, harmonics, optimal network configuration, network operation and development planning, are also very significant issues. Thus, it is necessary to use special and complex tools to resolve all these issues. The exposed material proves that the DMS is a unique powerful tool for coping with all these issues and realizing both noted imperatives.

In addition, DMS is the basic platform of SDG concept establishment. Thus, the following two conclusions can be stated:

The higher the quality of the applied DMS is, the smarter the distribution network is.

The smarter the distribution network is, the higher the GDG penetration limit can be achieved.

Acronyms

AVR – automatic voltage regulator
CB – capacitor bank
CHP – combined heat and (electric) power
DG – distributed generator
DLP – daily load profile
DMS – distribution management system
GDG – green distributed generator
LV – low voltage
LVL – lower voltage limit
MV – medium voltage
MicroFIT – micro feed-in tariff (generator)
PV – photovoltaic
SCADA – supervisory, control and data acquisition
SDG – smart distribution grid
SLVDC – single line voltage drop compensation
ULTCT – under load tap changing (supply) transformer
UVL – upper voltage limit
Var – reactive power
Volt – voltage
VR – (feeder) voltage regulator

Appendix

The volt control DMS power application is used as the first and the most important tool for elimination of network voltage limits violations caused by GDG operation. (The var control and volt/var control power applications are next. Their usage is not described due to lack of space in the paper.) Co-ordinated operation of ULTCT (supply transformers) and VR installed in depths of MV feeders (supplied by the ULTCT) is presented here. This coordination is provided by DMS. Both types of control devices are provided by AVR. Their constant set point voltage control laws, fig. 6(a), are remotely controlled and can be (re)set by SCADA system (*e. g.* thick and dashed line in fig. 6(a), with two different voltage set points U_{max1} and U_{max2}). A feeder presented at the top of fig. 6(b) is considered. It is supplied by a ULTCT. A single VR is installed in the depth of the feeder. Two GDG are connected to the first part of the feeder (the part between the ULTCT and the VR). The first GDG is connected between the secondary side of the ULTCT and the primary side of VR. The second GDG is connected at the primary side of the VR. The feeder‘s second part, which is fed through the VR, does not contain GDG. The feeder‘s loads are represented by arrows.

Let us consider the light sun (wind)/light load condition of the feeder. The constant set point voltage control laws of AVR of both ULTCT and VR are determined by DMS volt control application executed in study mode for this condition [22, 23] – thick line in fig. 6(a), the set point U_{max1}. The feeder voltage profile 1, fig. 6(b), represents the corresponding feeder steady-state operation. The voltage limits are not violated. The feeder voltage profile 2, fig. 6(b), represents the feeder steady-state operation in high sun (wind)/light load condition (both GDG operate with their rated powers), for the same voltage control laws set at AVR of both ULTCT and VR. The voltage limits in the first part of the feeder are violated due to the assumed high power operation of GDG and the same voltage set point of the ULTCT (U_{max1}). The steady-state voltages of the second part of the feeder are not changed due to the unchanged voltage at the VR secondary side (the set point of its AVR is not changed). The limit violation in the first part of the feeder can be assessed (in advance) by the DMS power flow power application executed in study mode for estimated GDG operation. The violation can be prevented in advance by (remote) resetting of set point of ULTCT‘s AVR from U_{max1} to U_{max2} – dashed line in fig. 6(a). The new set point U_{max2} is calculated by the DMS voltage control power application executed in study mode. The feeder voltage profile 3 represents the corresponding feeder steady-state operation. The voltages of the first part of the feeder stay within limits. Since the set point of the VR is not changed, the steady-state voltages of the feeder‘s second part stay unchanged.

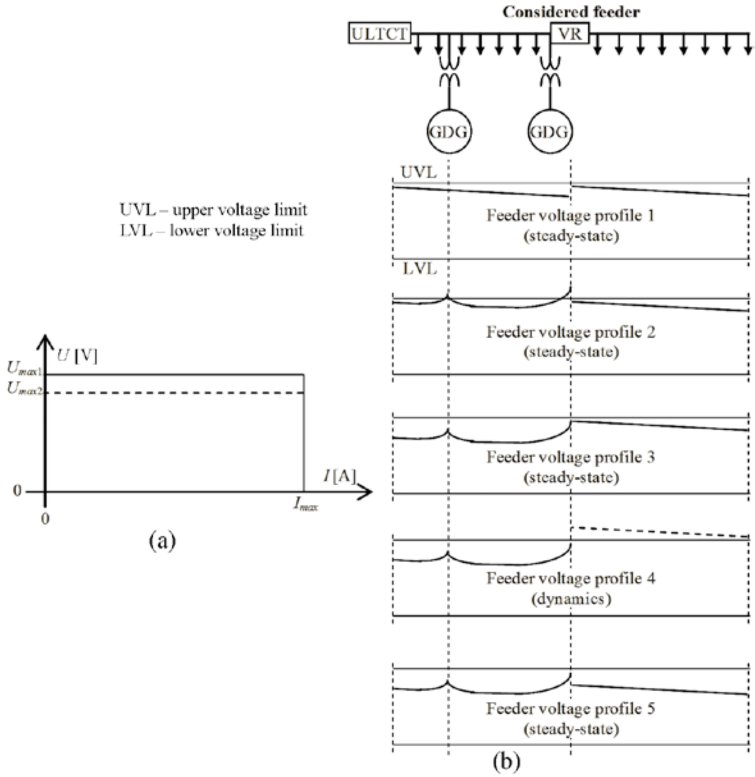

Figure 6. (a) Different settings of AVR of ULTCT and VR; (b) Corresponding effects

Let us now consider the dynamics between previously described steady-state effects of the voltage control (from voltage profile 2 to voltage profile 3). Let us assume that both GDG suddenly change from zero to rated power operation (*e. g.* due to a sudden change of the weather from light to high insolation in the case of solar GDG). The voltage profile of the second part of the feeder, for the time that is equal to the time delay T_d of the VR‘s AVR (between 10 and 100 s), is presented by dashed line in fig. 6(b) – feeder voltage profile 4. This voltage profile will change to feeder voltage profile 3 (second part of the feeder) after the time delay T_d. Thus, the upper voltage limit in the second part of the feeder will be temporarily violated (for time period equal to the time delay T_d). To prevent such violations, the VR‘s AVR has to be set in the same way as the ULTCT‘s AVR, *i. e.*, its voltage set point has to be decreased in advance for the same value as the voltage set point of the ULTCT‘s AVR. Thus, instead of the feeder voltage profile 3, the steady-state feeder voltage profile 5 (after time delay T_d) is ultimately established, fig. 6(b).

Finally, it has to be stressed that the replacement of the existing AVR of ULTCT and VR from constant voltage set point with the SLVDC type, will significantly relax the operation management of a distribution network in the presence of GDG.

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