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Effects of Distributed Generation on Voltage Profile for Reconfiguration of Distribution Networks

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***Abstract*—**Generally, distributed generation units refer to small-scale electric power generators that produce electricity at a site close to the customer or an electric distribution system (in parallel mode). From the customers' point of view, a potentially lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence can be the key points of a proper DG unit. Moreover, the use of renewable types of distributed generations such as wind, photovoltaic, geothermal or hydroelectric power can also provide significant environmental benefits. Therefore, it is of crucial importance to study their impacts on the distribution networks. A marked increase in Distributed Generation (DG), associated with medium voltage distribution networks, may be expected. Nowadays, distribution networks are planned for unidirectional power flows that are peculiar to passive systems, and voltage control is carried out exclusively by varying the tap position of the HV/MV transformer. This paper will compare different DG control methods and possible network reconfiguration aimed at assessing their effect on voltage profiles.

***Keywords*—**Distribution Feeder Reconfiguration (DFR), Distributed Generator (DG), Voltage Profile, Control.

I. Introduction

OVER the last decade, distribution systems have seen a significant increase in small-scaled generators as they can compensate the disadvantages encountered in the centralized generation dispatch. These generators, also known as distributed generation (DG), are installed in the network to serve as a source of power at on or near the site where they are to be used. They can be driven by different types of resource and technology such as wind, solar, fuel cells, hydrogen, and biomass. The introduction of DG units brings a number of technical issues to the system. Many technical effects of distributed generators on the distribution system have been reported in literature such as thermal rating of equipment, system fault levels, stability, reverse power flow capabilities of tap-changers, line drop compensation, voltage rise, power losses, power quality (such as flickers and harmonics) and protection. The need to reduce pollution of the environment has led to growing worldwide interest in the introduction, in distribution networks, of small and medium-sized generators that utilize primary renewable energies. However, new technologies involving the use of conventional fossil fuels, such as fuel cells and micro-turbines, have also been the subject of research, since they offer the prospect of a significant reduction in pollutant emissions. Thus numerous steps are being taken and research projects launched with a view to introducing Distributed Generation (DG) in electricity networks.

An area of special interest is that of the combined production of electric power and heating, since this result in a worthwhile reduction in primary energy and, therefore, lowers consumption and pollutant emissions. Given the difficulty of thermal power transmission, such plants have to be located near the places where there will be a use for the heating generated, so as to be able to exploit to the full all the advantages offered; this will involve the presence of a large number of generators, distributed throughout the network. Thus it becomes necessary to integrate all the generators with the distribution network in order to achieve an improvement in the quality of the power supplied in relation to the reliability of the electricity system. In this connection, a large number of research projects are under way in order to look into the various possibilities that Distributed Generation can offer, not only as regards power supply, but also with reference to ancillary network services [1]. This is to a great extent influenced by the type of technology employed and the type of primary energy source. It is not therefore possible to conduct general research covering all types of DG, but each study will have to consider one alternative or the other.

Another factor that determines the success of DG or of one technology rather than another is the deregulation of the electricity market and of the rules that govern it. Currently, there are no rules devoted exclusively to DG, with the result that small producers confine themselves either to their own production or to the sale of electric power only, without caring too much about the quality of the service. This is due to the fact that small producers have no power to compete in a market dominated by a few big companies. Nevertheless, extensive penetration by DG might lead to the definition of new rules that would enable better advantage to be taken of the opportunities on offer.

The purpose of this paper is to consider voltage controls in distribution networks. At the present time, regulation takes the form of varying the transformation ratio of HV/MV transformers by means of Under-Load-Tap-Changers (ULTC) by keeping the voltage fixed at a given place in the network, generally at the MV busbars of the primary sub-station. However, this regulation philosophy, which has imposed itself through being easy to operate, does present a number of drawbacks. Above all, if the network is very big, voltages may vary greatly between the beginning and the end of lines. Moreover, the variability of the load during the day will compel

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the regulator to carry out a large number of switching operations on the ULTCs – a typical example might be about 70 per day – resulting in rapid deterioration and the need for frequent maintenance.

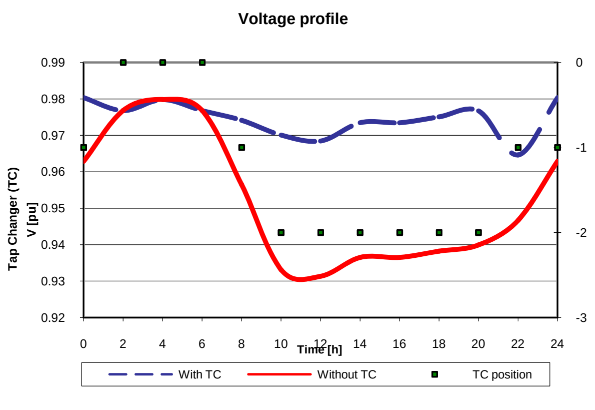
II. Voltage Profiles in Medium Voltage Distributions Network

An important factor in the quality of electric energy is the stability of the voltage in the network, which has to be kept as far as possible close to the rated value in order to ensure the normal operation of users' equipment. Indeed, the more and more widespread use of electronics increases the sensitivity of user equipment to voltage quality [2]. The causes of variations in the voltage of a network are many and of various kinds, but are mainly due to variations in the load. Other causes may be transient events such as atmospheric phenomena or protection trip in the network.

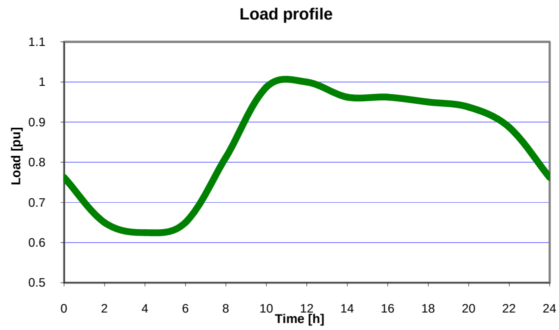
Expression (1) gives the value of the voltage drop in a line with resistance R and reactance X transmitting active power P and reactive power Q. Unlike HV transmission lines, in which resistance is negligible compared with reactance, in MV distribution lines the two contributions are comparable, so that both the flows of active power and those of reactive power make a significant contribution to the voltage drop.

$$\Delta V_{\%} = \frac{R \cdot P + X \cdot Q}{V^2} \cdot 100 \qquad (1)$$

The variability of the load is therefore the primary cause of voltage fluctuation in a network. It might be decided to control this variation by as far as possible levelling the load diagrams: that is, by making the demand for power on the network more uniform as between day and night. However, such a step is very difficult to implement in distribution networks, both because of their vicinity to the loads and due to the difficulty of creating efficient storage systems. There is therefore a tendency to limit this effect by compensating for the voltage drop by varying the transformation ratio of the HV/MV transformer.



(a)



(b)

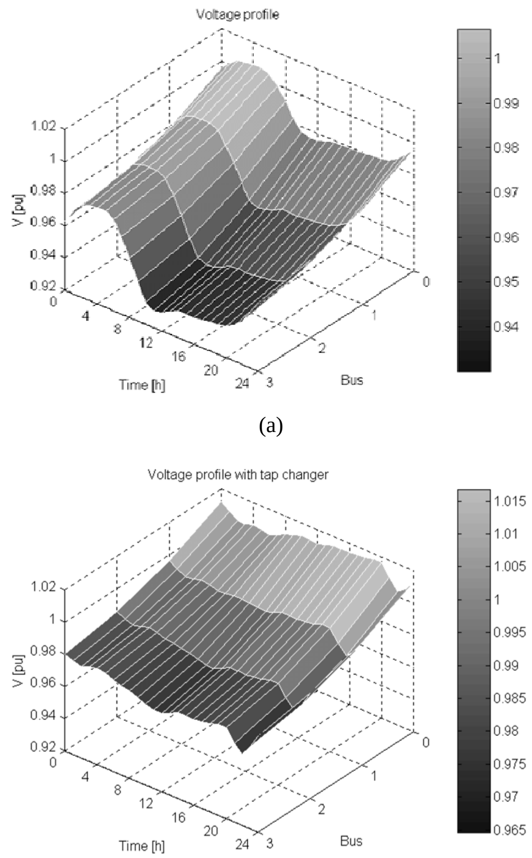
Fig. 1 (a) Estimation of the hourly voltage in an MV node with and without regulation (with a tap-changer step equal to 1.5% V_n) - (b) Load diagram

Fig. 1 (a) shows the voltage diagram in a node of a 20 kV distribution line in the course of one day: the opposite trend to the load diagram (Fig. 1 (b)) makes the linear approximation of the voltage to the load acceptable in (1). Since it is best for the voltage change allowed in medium-voltage (MV) lines to be within ±4% so as to avoid excessive drops in the low-voltage (LV) section, it will be noted that, in the absence of any steps being taken to regulate (unbroken line), the voltage diminishes during the day – that is, during the period of higher absorption – to values unacceptable for the correct operation of equipment. This makes it necessary to increase the size of the line in order to reduce impedance and bring the voltage drop down to acceptable levels. On the other hand, the introduction of regulation systems at the primary sub-station based on the use of ULTCs permits more effective levelling of the voltage profiles over time.

If we look at the graph in Fig. 1, it would therefore seem that the variation in the transformation ratio of the HV/MV is sufficient to solve the problems involved in regulating the voltage of distribution networks. This is partly true since, to date, it is the only means of regulation that has been used, but it presents a number of drawbacks. Above all, it is a discrete regulation system: that is, it is possible to set up only finite voltage values; this means that in order to obtain sufficiently fine-tuned regulation many steps are needed, so that the tap-changer is forced to perform a large number of operations during the day. In addition, it is a system that regulates the voltage at *one point only* in the network, generally at the MV busbar of the primary sub-station, thus leaving the voltage drops unchanged along the lines.

Fig. 2 shows the voltage diagram along a 20-kV line in the absence (a) or in the presence (b) of a regulation system. The line consists of 3 lengths, each with a resistance of r = 0.226 Ω/km and reactance of x = 0.384 Ω/km; each node is connected to a load that absorbs P_{max} = 2.25 MW and Q_{max} = 1.125 Mvar, with a load diagram trend shown in Fig. 1 (b).

The use of ULTC at the primary sub-station greatly improves the trend along the time axis, but the voltage drop along the line remains almost the same. If the network were a very large one and the lines very long, there might be an unacceptable voltage towards the end of the line despite the presence of a regulation system. It will therefore be necessary to have an oversized line in accordance with the criterion of the maximum voltage drop allowable in order to conform to the limits imposed by the regulations.



(a)

(b)

Fig. 2 The space-time diagram of the voltage along a line without (a) and with (b) regulation

III. The Influence of Distributed Generation on Voltage Profiles

So far the main role of distribution networks has been to interconnect central generation and transmission network with the end users, and thus they have always been considered passive networks. The widespread use of generating systems at user level is now changing their nature from passive to active [3] and therefore their role.

Thus, the network has not only a power distribution function, but also the job of despatching and controlling DG in order to ensure the reliability and smooth working of the electric power system. In this context, which is new for networks and of which there has not yet been any practical experience, nor a serious attempt made to draw up regulations, it becomes necessary to make a careful appraisal of the impact that DG may have on the electric power system.

An important aspect to consider is the influence of DG on the voltage profiles of lines. Indeed, the presence of a generator in a network causes a general increase in the voltage; while, on the one hand this is favourable in terms of the increase in the margins available and the reduction of losses, on the other it may lead to over-voltages, especially in the vicinity of the DG's connection point [4]. A first practical rule in order to obtain an improvement in the voltage profiles of a uniformly-loaded line is the "2/3 rule" described in [5]. This consists in inserting, two-thirds of the way along the line, a generator with a power equal to two-thirds of the total load of the line. However, on the assumption of extensive penetration by DG, when both the place and the power are decided by the producer, this type of approach is no longer possible.

The problem of controlling the voltage in the presence of DG is not limited to the alteration of power flows, but has also to take into account the influence of the generators on the regulation systems present. In this connection, [6] analyses the influence of DG on a regulator carrying out load compensation. In maximum load conditions, the action of the regulator on the ULTCs is such as to maintain, at the beginning of line, a higher voltage level in order to obtain an acceptable value at the end. The presence of a generator immediately downstream means that the load, as seen by the regulator, is lower, and consequently the compensation effected is smaller; the final effect is therefore that of having a general lowering of the voltage on the line to such an extent that it exceeds admissible limits.

Lastly, [7] suggests an algorithm controlling the ULTCs that, faced with an increase in the number of operations, improves the performance of the voltage profiles in the network in the presence of distributed generating and storage systems.

IV. Constant Power Factor Control of Distributed Generation

Constant power factor control of DG is the type nowadays most widely used, for both technical and financial reasons. Indeed, many of the generators used in DG systems have no regulation capacities of their own; this applies, for example, to wind-energy generation, which uses asynchronous generators or static ones interfaced with the network by means of line-commutated converters. None of these systems are able to sustain the voltage by themselves, and can only operate in parallel to the network. But even in the case of synchronous generators or switch-mode converters, there is no sort of regulation, since, in general, this is more costly and the service is not at present paid for. Nevertheless, it is possible to improve the voltage profile of a line by, whenever possible, positioning the generator correctly.

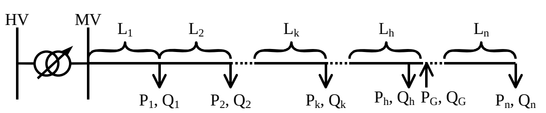


Fig. 3 Distribution network with several loads, with DG inserted at node h

Let us now consider the voltage drop in the line in Fig. 3 at point k, assuming that h has a generator supplying active power P_G and reactive power Q_G; we have considerate, besides, r and x as resistance and reactance values per unit of length of the line, L_i as the length of the i^{th} section and P_i and Q_i as the active and reactive power absorbed by the i^{th} load.

Equation (1) is a linear relationship in P and Q, since the voltage changes, assumed to have been limited to ±4%, are negligible; therefore the load variations are proportional only to the current variations. It is therefore possible to apply the principle of superimposition of the causes and effects, by considering first the contribution made by the loads and then that made by the generator. By resorting to (1), we find that the voltage drop at k, due to the loads alone is expressed by:

$$\Delta V_{Lk} = \frac{\sum_{i=1}^{k}\left[r \cdot L_i \cdot \left(\sum_{j=i}^{n} P_j \right) + x \cdot L_i \cdot \left(\sum_{j=i}^{n} Q_j \right) \right]}{V^2} = \lambda_k \tag{2}$$

If we now consider the effect at k of only the generator inserted a h, we find that:

$$\Delta V_{Gkh} = -\frac{\sum_{i=1}^{\min(h,k)} \left[r \cdot L_i \cdot P_G + x \cdot L_i \cdot Q_G \right]}{V^2} = -\gamma_{kh} \tag{3}$$

ΔV_{Gkh} is negative because, generally speaking, the generator causes the voltage to rise. This may not always be so, however; for example, generators that cannot, of their very nature, sustain the voltage, as do asynchronous generators, have to absorb the reactive power needed for their magnetization (the term Q_G is negative): if the line were mainly inductive, then ΔV_{Gkh} would become positive, that is, the generator would actually cause a voltage drop.

The total voltage drop at point k will therefore be equal to the sum of the two effects:

$$\Delta V_k = \Delta V_{Lk} + \Delta V_{Gkh} = \lambda_k - \gamma_{kh} \tag{4}$$

The optimal position h of the generator is obtained by minimising the maximum voltage drop; the objective function therefore becomes the following:

$$\min_h \left(\max_k \left| \lambda_k - \gamma_{kh} \right| \right) \tag{5}$$

Let us consider the line in the example given in Fig. 2, in which we will insert a generator supplying the powers P_G = 5 MW and Q_G = 2.5 Mvar; that is, equal to 2/3 of the maximum power of the line. Of the three positions possible, it is a matter of estimating the one that will reduce the voltage drop to a minimum. To do this, we apply (4) for each position of the generator and for each load value during the day; Table I shows the maximum voltage drop at any node k in the course of one day as a function of the generator's position.

TABLE I
VOLTAGE DROP (PU) AT THE NODES OF THE LINE FOR DIFFERENT GENERATOR POSITIONS

Node \ Gen.Pos.	1	2	3
1	0.0055	0.0055	0,0055
2	0.0196	–0.0084	–0.0084
3	0.0266	0.0110	–0.0195

The objective is to minimise the maximum voltage drop: that is, to apply (5). For each position of the generator we have to take the maximum value of the module of the voltage drop as shown in Table I. From among the maximum values we select the minimum; therefore the optimal position for the generator is node 2.

The space-time diagram of the voltage along the line shown in Fig. 4 indicates how insertion of the generator, combined with a regulator at the primary sub-station, considerably improves the voltage profiles; this is clearly shown by the fact that the surface has become flatter.

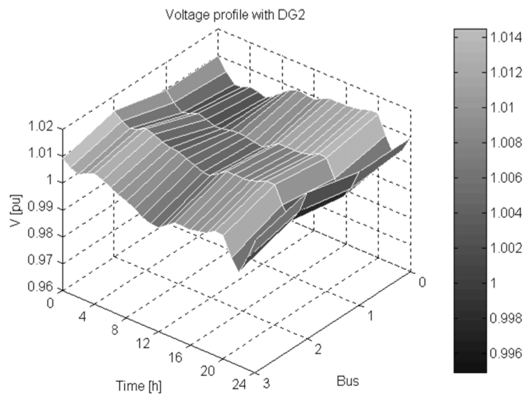


Fig. 4 Space-time diagram of the voltage along a line with constant power factor control DG inserted at node 2.

V. CONSTANT VOLTAGE CONTROL OF DISTRIBUTED GENERATION

As has been said, voltage regulation is mainly implemented at the primary sub-station by taking action on the ULTC of the HV/MV transformer. However, we have seen that, at times, it is essential to regulate the voltage at other points in the network too. This is sometimes done by inserting, in the HV/LV sub-stations, fixed or variable capacitor banks that will compensate for the load's reactive power; but this is not always effective, since the reactive power produced depends on the square of the voltage, and therefore tends to emphasise the drop or the overvoltage.

The insertion of generators in the distribution network may make it possible to set up continuous voltage regulation. As we have also said, generally speaking, constant-voltage control of the generator is more costly, but in the long run extensive penetration by DG might become cheaper, at least for some of them. Voltage control is achieved by varying the reactive power produced by the generator; the active power is often imposed by other constraints: for example, through the production of thermal energy for co-generation plants, which means that it has to be kept constant.

As in the previous case, we want to evaluate the optimal generator position that will minimise the voltage drop on the line. With reference to Fig. 3, it may be pointed out that, in position h in which the generator is inserted, the voltage change is imposed by the generator and is therefore constant and set equal to $\Delta V_h = V_n - V_h = -\sigma_h$ (in which V_n is the rated voltage and V_h is the voltage imposed in the node connecting the generator), to which the expression $\lambda_h - \gamma_{hh} = -\sigma_h$ corresponds. By making the two terms equal we can obtain the expression for the reactive power that the generator should supply to keep the voltage constant:

$$Q_{GhT} = \frac{\sum_{i=1}^{h}\left\{ r \cdot L_i \cdot \left[\left(\sum_{j=i}^{n} P_j\right) - P_G\right] + x \cdot L_i \cdot \left(\sum_{j=i}^{n} Q_j\right)\right\} + V^2 \cdot \sigma_h}{x \cdot \sum_{i=1}^{h} L_i} \quad (6)$$

The value Q_{GhT} thus calculated has to be compared with the maximum reactive power Q_{Gmax} that the generator is able to supply. In the ultimate analysis, the value Q_{Gh} that the generator has to produce is equal to:

$$Q_{Gh} = \min\left(Q_{GhT},\ Q_{G\max}\right) \quad (7)$$

At this point we proceed as in the previous case, selecting on each step the reactive power supplied by the generator calculated by means of (4).

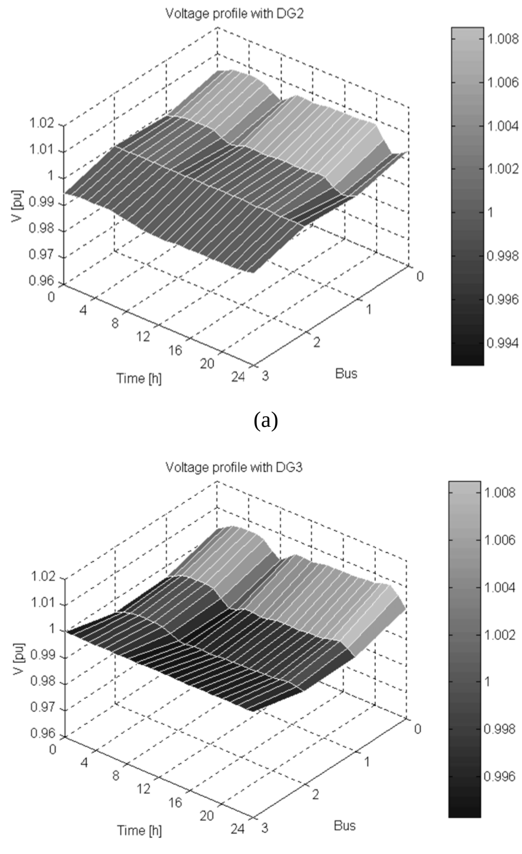
As in the previous case, let us consider the line in the example in Fig. 2, in which it is intended to insert a generator with a power of P_G = 5 MW with Q_{Gmax} = 3.75 Mvar ($\cos\varphi$ = 0.8). Moreover, it is assumed that we want to keep the rated voltage at the node where the DG is inserted, to which $\sigma_h = 0$ corresponds. By carrying out the procedure described we obtain the results in Table II.

TABLE II
MAXIMUM VOLTAGE DROP(PU) AT THE NODES OF THE LINE IN RESPECT OF DIFFERENT GENERATOR POSITIONS WITH CONSTANT VOLTAGE CONTROL AND MAXIMUM REACTIVE POWER SUPPLIED(MVAR)

Node \ Gen.Pos.	1	2	3
1	0	0.0035	0.0071
2	0.0141	0	0.0071
3	0.0212	0.0071	0
Q_G [Mvar]	4.4049	3.1803	1.9557

In this case, we should have two good positions: 2 and 3; however, in position 3, the generator has to supply a lower quantity of reactive power and is therefore less stressed. In position 1, on the other hand, the generator ought to exceed the maximum limit of Q_G allowed, and therefore could not keep up the required voltage.

Examination of the graph in Fig. 5 shows that constant voltage control further improves the voltage profiles along the line, but that, especially with changes in the load, it maintains the voltage most stable at the node where the generator is inserted. This is an advantage, especially for the MV/LV sub-stations, because the transformer is fitted with a transformation ratio variation that functions off load, and therefore allows only a limited number of operations.



(a)

(b)

Fig. 5 Space-time diagram of voltage along a line with DG inserted at node 2 (a) and node 3(b) with constant voltage control

VI. RECONFIGURATION OF THE DISTRIBUTION NETWORK

MV distribution networks are generally operated with a radial system that makes for simplicity in the management of the power flows and the possibility of finding faults without delay. On the other hand, they offer little chance of improving the quality of service to any appreciable degree.

The layout of MV Distribution Networks varies greatly, but in general they all offer the possibility of alternative supplies to lines, so that a faulty line section can be isolated without interrupting the supply to the loads. The networks therefore consist of line sections that may be connected to each other in various ways; in other words, the network can be reconfigured as necessary.

The reconfiguration of lines is a very important function in automated distribution networks. Its purpose is mainly that of improving the quality of service, reducing losses, and boosting the reliability of the network [8]. In present-day networks the process of reconfiguration is carried out while keeping the radial layout, since existing protective systems would not allow correct selectivity in meshed systems.

As we have seen, the presence of a generator has a considerable influence on voltage profiles along a line, both positively, but also negatively if the necessary steps are not taken. For example, if the power injected is much higher than that absorbed by the loads along the line, over-voltages may occur at the point of connection of the generator. In this case, it may be a good idea to reconfiguration the network in such a way as to redistribute the power flows, thus levelling the voltage profiles.

Let us consider the network in Fig. 6, consisting of two lines that are equal both in their parameters and in their loads to the previous examples, in which the possibility of an alternative supply exists: in the absence of DG, this is operated radially, with the lines L_1 and L_2 separate and directly connected to the busbar of the HV/MV primary sub-station.

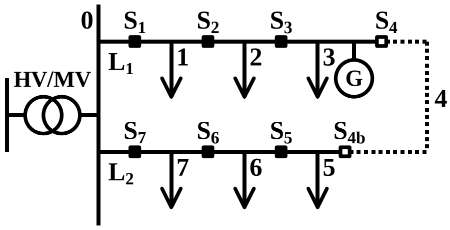


Fig. 6 Example of reconfigurable network

The voltage profile of L_1, which is equal to that of L_2, is shown in Fig. 7 (a), and is sufficiently flat to conform to the limits imposed by regulations.

Now let us assume that we want to insert in 3 two 5 MW groups with a power factor of 0.9; that is, with total power exceeding the line's total load, but such as not to overload the line. The power flow has now been inverted, and the voltage at the end of L_1 is consequently greater than at the beginning and such as to cause over-voltages that are unacceptable for the proper operation of the electric power system (Fig. 7 (b)).
On the other hand, as regards line L_2, no changes in the voltage profiles are noted (Fig. 7 (c)).

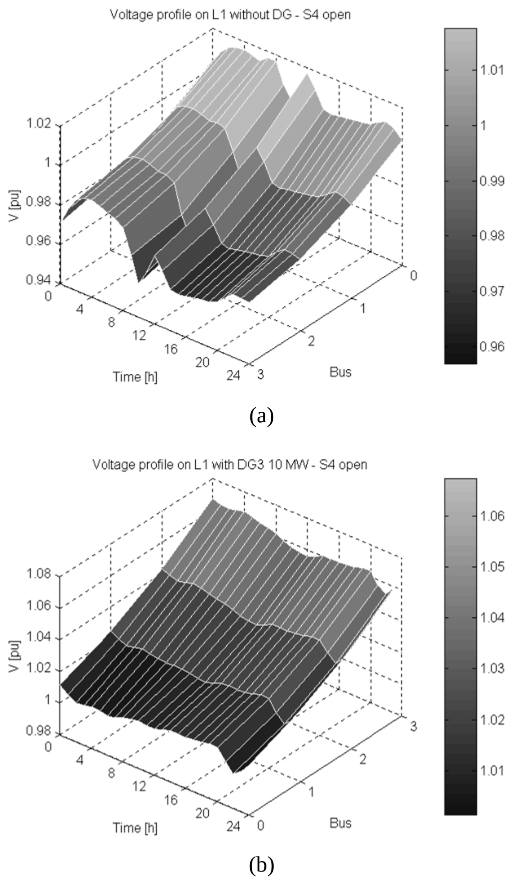
We now wish to investigate whether a suitable reconfiguration of the network, and therefore redistribution of the power flows, may improve the voltage profiles in such a way as not to present either excessive voltage drops or over-voltages. To do this, it is necessary to assess the variation in the maximum voltage ΔV_k in the various nodes of the network in the course of one day, on the assumption that part of the loads has to be deviated from line L_2 to line L_1 by acting on the circuit-breakers S_i in Fig. 6.

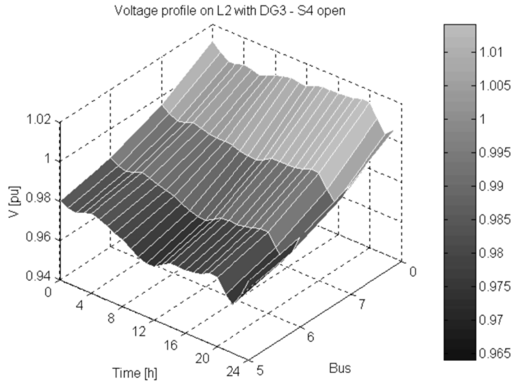
From (2) we may deduce: $\Delta V_k = \lambda_k - \gamma_{k3}$, in which γ_{k3} is the effect at *k* of the generators connected to node *3*. By applying this formula for different reconfigurations of the network we obtain the results given in Table III. The optimal network configuration, that is the one that minimizes voltage variations at the nodes, is the one that involves shifting loads *5* and *6* from line L_2 to line L_1 (Fig. 7 (e)).

TABLE III
MAXIMUM VOLTAGE DROP(PU) AT THE NODES OF LINE L1 FOR VARIOUS CONFIGURATIONS WITH DG LOCATED IN 3

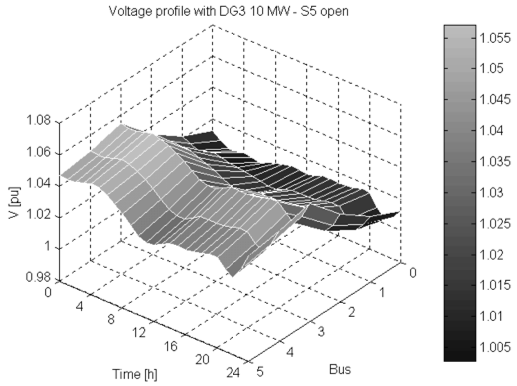
Loads connected \ Node	1	2	3	5	6	7
1 ÷ 3	0.0176	0.0398	0.0665	–	–	–
1 ÷ 5	0.0128	0.0301	0.0521	0.0473	–	–
1 ÷ 6	0.0080	0.0205	0.0376	0.0280	0.0232	–
1 ÷ 7	0.0121	0.0171	0.0232	0.0372	0.0521	0.0595

The transfer of load *5* only would not enable the voltage to be lowered sufficiently at node 3 (Fig. 7 (d)); on the other hand, the total shifting of the loads from L_2 to L_1 would cause a substantial lowering of the voltage in nodes 5, 6, and 7 (Fig. 7 (f)), since there would be an incorrect distribution of the power flows. If adequate reconfiguration of the network were not possible, it would be necessary to reduce the maximum injectable power of the generator, or else to adapt line L_1 to the new requirements.





(c)



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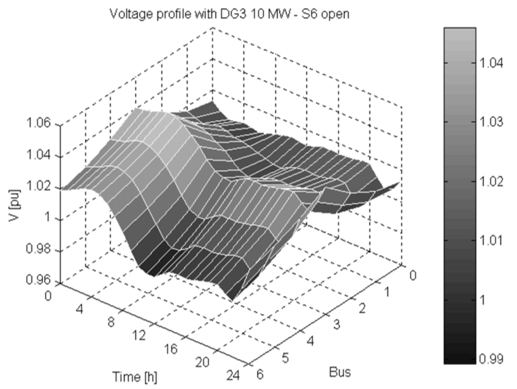

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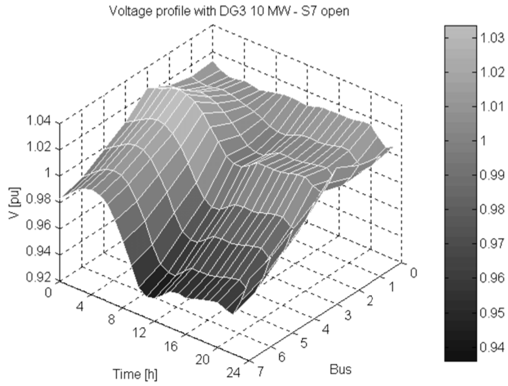

(f)

Fig. 7 Diagram of the voltage profiles in lines L_1 and L_2 in the absence of DG (a), with DG in 3 (b), (c) and with a reconfigured network (d), (e), (f)

VII. Conclusions

The introduction of generators into distribution networks built and operated in such a way that they are passive, alters the power flows and consequently the voltage profiles.

This paper has analyzed the optimal positioning of the generators in a network and the effect that the type of control has on improvement of the voltage profiles. There is no general rule, but better positioning has to be examined on a case-by-case basis, depending on the type of network, the type of load, and the regulation systems already present.

It has been pointed out that the correct positioning of the generators may lead to an improvement in the voltage profiles, both in terms of space (along the line) and in terms of time (with variations in absorption). In the second case, a decisive factor is the type of generator control: indeed, as we have seen, constant voltage control greatly reduces the voltage variations during the day, but is generally speaking more expensive to operate than constant power factor control. How economical it is will therefore depend on the sensitivity of the loads to voltage variations.

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