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Power electronics applied to voltage control in rural distribution networks with penetration of distributed generation

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Abstract. In rural distribution networks with widely dispersed loads, characterized by the utilization of long overhead lines, voltage profiles with big variations appear along the line due to the significant variations of the load between peak hours and valley hours.

This paper describes the problems that the integration of distributed generation based on renewable resources could generate in that scenario, and presents solutions that are commonly used to mitigate these problems and proposes new solutions to solve them.

The integration of distributed generation (DG) based on renewable resources in these networks increases the variability of the voltage, and in some cases the power flow of the network also can be bidirectional. Usually this integration of distributed generation is limited by the network operator limiting the maximum voltage variation produced by the distributed generation in the point of common coupling (PCC).

In this paper different traditional methods for voltage control are described and analyzed for a widely dispersed rural network scenario.

The impact of the DG in these methods of voltage control and the advantages of power electronics in this new scenario are exposed. Power Electronic devices applied to these distribution networks allow more efficient management of the network increasing the integration of distributed generation maintaining the security levels.

Key words

Voltage Control, Distributed generation, SVR, STATCOM y Overhead lines.

1. Introduction

The rural distribution networks are characterized by the utilization of overhead lines [1] with widely dispersed loads, with large fluctuations of consumed power between peak hours and valley hours. Due to that the voltage profile is highly variable along the day.

The grid codes set the minimum and maximum voltage level of all the nodes. In Europe there are different grid codes depending on the country, for example in Spain a voltage limit of 7% is established for the voltage [2].

In rural distribution networks the voltage in the nodes can violate the limits established due to the length of the lines, usually these lines can be of tens of kilometers or more. For avoid these problems the distribution network operators (DNOs) install devices like OLTCs (On-Load Tap Changing Transformers), SVRs (Step Voltage Regulators), capacitor banks, STATCOMs (Static Synchronous Compensators) along the lines, which help to keep the node voltages within the established limits.

In this paper the traditional voltage control in rural distribution networks is analyzed and simulated. Then a voltage control method based on power electronics is exposed analyzing the optimal placement of the power electronic devices. Also the traditional voltage control with penetration of DG is tested and compared with the voltage control based on power electronics. Finally a voltage control based on the combination of the SVR and the statcom is proposed and simulated.

2. Voltage control in rural distribution networks

A. *Traditional voltage control elements*

The On Load Tap Changer (OLTC) is a device which has been usually installed at the header of the substation. It is a transformer which connects the distribution network (Medium voltage network) with the transmission network (High voltage network), but as it can be seen in its name, it has the capacity to change its transformation relation, changing the voltage level in the distribution network.

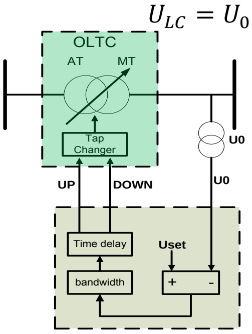
These transformers can be controlled in two ways, through a Load Tap Changing (LTC) control or through a Line Drop Compensation (LDC) control. The LTC controls the output voltage of the transformer maintaining the voltage within the limits specified by the codes (1), the control scheme can be seen in the Fig1, [3].

$$U_{LB} \le U_0 \le U_{HB} \quad (1)$$

The LDC maintains the voltage of the furthest load node of the network within the limits specified by the codes. This control is a feed-forward control, Fig2, which needs the approximated value of the resistance and the inductance of the line. The poor fit of Rset and Xset involves a bad control of the voltage in the furthest load node, as is exposed in [4].

$$U_{LB} \leq U_{LC} \leq U_{HB} \qquad (2)$$

$$U_{LC} = U_0 - I_0 \times (R_L + j \times X_L) \qquad (3)$$



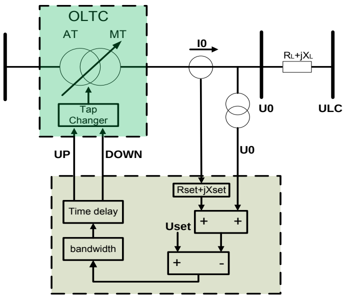


Fig 1. LTC Control Fig 2. LDC Control

Both controls could be used on OLTCs, but the LDC is usually disabled. Although these transformers are able to change its transformation relation on load, actually they try to minimize the number of changes. The reason for that is the relationship between the life of the transformer and the number of tap changes: the increase of on load changes decrement the life of the transformer.

The coordination of the OLTCs with other distributed devices for voltage control is being widely analyzed and researched. For example, in [3] a coordinated control between an OLTC and a STATCOM installed in a substation is presented. Another coordinated control between an OLTC and a STATCOM is presented in [5].

Other magnetic device that is usually used in rural distribution networks is the SVR. The SVR is an autotransformer which is installed along the distribution line to change the voltage downstream [6]. As in the OLTCs, the SVR could be controlled using LTC or LDC control. In practical cases the most used control is the LDC, controlling the voltage on the furthest load node of the line. Depending on the characteristics of the line and the specifications the SVR can be connected in Delta or in open Delta.

Much research is being carried out analyzing the benefits of coordinated control between SVR and capacitor banks [7].

The rural distribution networks usually are meshed networks but are operated radially [8]. Overhead lines are normally used in these networks, and they are usually long lines from 30 Km to 120 Km of separated bare or insulated conductors. The impedance of the line per kilometer can be calculated through the characteristics of the conductors and separation of them.

B. Proposed scenario

The proposed scenario is a rural dispersed network of 30kV-s, formed by 8 transformation centers (CT) of 630kVA each one which consume power with a power factor greater than 0.9. This is because the CTs with low power factor usually have capacitor banks to avoid penalties. In this scenario the power factor limit is set to 0.9. The CTs are installed every 14Km, so the total line length is 112Km (see Fig 3).

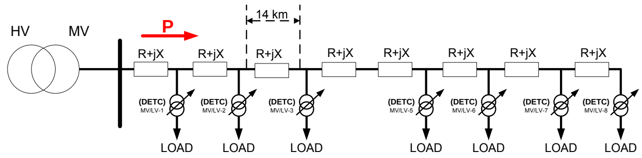


Fig 3. Selected Scenario

The standard values in overhead lines of medium voltage are X = (0,3-0,4) Ω\Km and X\R = 1,2 [8]. In the scenario the conductors are Prysmian CCX 94-AL1/22-ST1A conductors, separated by 1.44m.

Table I. Characteristics of the line

Nominal Voltage	Electric Resistance at 20ºC	Electric Reactance
30kV	0.3067Ω/Km	0.365Ω/Km

To calculate the voltage drop in a distribution line Power Flow calculations are used. These calculations are based on numerical methods: The most used are the Newton-Raphson method, the Blackward-Forward method (for radial networks), the Gauss-Seidel methods, Fast Decoupled Method (FDM) and the Iwamoto's method, but essentially all of them are based on electrical equation [9]:

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_{i,prog} - jQ_{i,prog}}{V_i^*} - \sum_{\substack{n=1 \\ i \neq n}}^{N} \left(Y_{n,i} V_n\right)\right] \qquad (3)$$

The modeling of the proposed system is based on these electrical equations solved by the Gauss-Seidel method [10]. This method needs initial conditions (V(0) and the powers consumed or generated in the nodes), and through iterations solves the equations achieving the real voltages of the system. This method has been selected for its simplicity and easy implementation on numeric software as MATLAB.

Starting from the assumption that the voltage of the PCC between the distribution network and the transmission network remains constant at nominal level, a simulation of the selected scenario at the moment of maximum power consumption has been done, Fig 4.

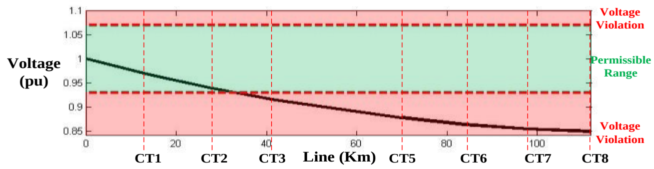


Fig 4. Voltage Profile of the selected scenario

All the values are presented in pu. The base of voltage is the nominal voltage of the line (30kV), and the base of power is 1MVA.

As shown in Fig 4, the voltages of the CT-s from 3 to 8 are under the low limit of voltage. To solve this type of problems the distribution network operators install the devices mentioned above.

C. Voltage control using magnetic elements

As mentioned in the introduction, the connection of an OLTC at the header substation makes possible to increase or decrease the voltage of the feeder, maintaining the voltage of all of load nodes within limits. The connected OLTC is a transformer of 10MVA with the characteristics specified in the Table II.

Table II. Characteristics of the OLTC

Primary winding voltage	Secondary winding voltage	Secondary winding controlled voltage	Impedance
120kV	27.9kV	4.2kV	0.01+0.08j pu

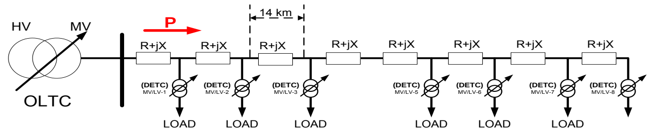


Fig 5. Selected scenario with OLTC

The OLTC as described above is a device which controls the voltage downstream it. The moment of maximum power consumption has been simulated, and as shown in Fig 6 even connecting the OLTC at its maximum transformation relation there is an undervoltage problem at the last nodes of the feeder.

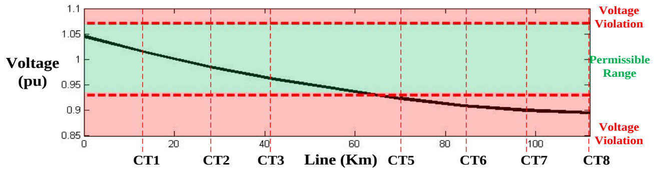


Fig 6. Voltage profile of selected scenario with OLTC

The voltage in CT5-8 is under established limit, so it is necessary to install some other device to increase the voltage level of these nodes. The SVR is the typical solution as mentioned in the introduction.

The selected SVR is a 3.3MVA SVR, with a variable transformation relation of ±10% as shown in Fig 7. It is necessary to change a little bit the OLTC set point when the SVR is installed in the line to avoid the overvoltage in minimum power consumption moments, so the transformation relation of OLTC has been changed to 31.5kV.

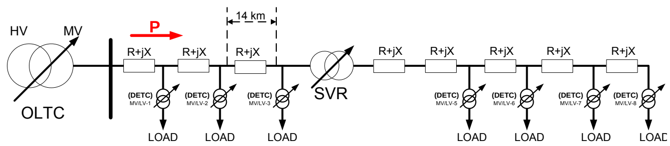


Fig 7. Selected scenario with OLTC and SVR

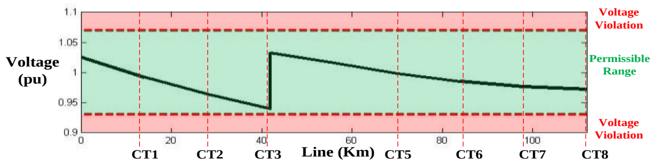


Fig 8. Voltage profile of selected scenario with OLTC and SVR

The voltage profile of the line is within the voltage limits established by grid codes in the moment of maximum power consumption.

3. Voltage control in rural distribution networks with power electronic devices

STATCOMs or SVCs are power electronic devices which inject reactive power to the grid to improve the power factor or increase/decrease the voltage level of the grid. These devices allow a continuous control of voltage and power factor, unlike all the devices mentioned above that only can implement discrete controls. In networks with high penetration of distributed generation, a solution based on power electronics can be a better solution than the solutions based on magnetic elements due to its better dynamic response, as it is going to be shown in this paper. These solutions based in power electronics are the alternative to the traditional solutions used in Medium Voltage lines as SVRs or capacitor banks, but can be also a complement to traditional solutions improving the voltage control.

An optimal placing of these devices is essential to take all the advantage of them. In this paper, the optimal placing of a STATCOM is analyzed, based on the equivalent impedance circuit, Fig 9.

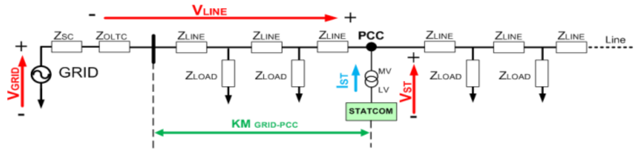
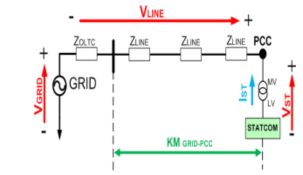


Fig 9. Impedance Circuit of the Fig 5

Taking the assumption that the load impedances are much bigger than the line impedances, the effect of the loads connected to the line could be neglected and the approximated circuit shown in Fig10 is obtained.



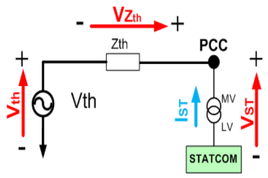


Fig 10. Approximated circuit
Fig 11 Thevenin circuit

From this approximated circuit the equivalent Thevenin circuit of Fig 11 can be created, in which Vth and Zth are the equivalent Thevenin voltage and the equivalent Thevenin impedance from the point of view of the STATCOM. Assuming that the grid voltage is 1p.u., the following equations can be derived:

$$V_{th} = 1 \quad (4)$$

$$Z_{th} = Z_{OLTC} + f(KM_{GRID-PCC}) \quad (5)$$

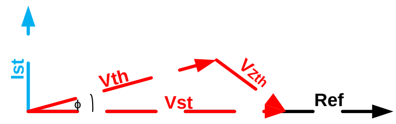


Fig 12. Vector diagram of the Thevenin circuit

Fig 12 shows the vector diagram of the simplified Thevenin circuit, where Vst refers to the voltage at the connection point of the STATCOM. It can be seen that the current injected by the STATCOM is 90º phase shifted with respect to this voltage, because the STATCOM works injecting (or absorbing) reactive power. It can be shown that:

$$V_{ST} = V_{th}\cos(\varphi) + Z_{th} I_{ST}\cos\left(\text{ang}(Z_{th}) - \frac{\pi}{2}\right) \quad (6)$$

$$0 = V_{th}\sin(\varphi) + Z_{th} I_{ST}\sin\left(\text{ang}(Z_{th}) - \frac{\pi}{2}\right) \quad (7)$$

$$|\Delta V| = |V_{ST}| - |V_{th}| \quad (8)$$

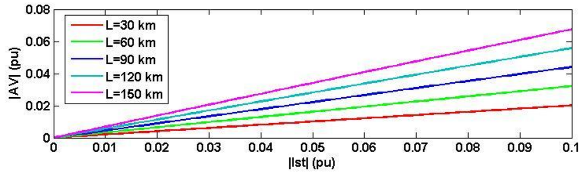


Fig 13. |ΔV| in function of the current of the STATCOM

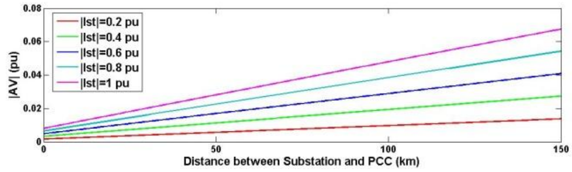


Fig 14. |ΔV| in function of the distance PCC-substation

Fig 13 and Fig 14 show that the variation of the voltage |ΔV| at the connection point of the Statcom (PCC) increases when the current of the STATCOM increases and also when the distance between the PCC and the substation increases. Therefore, it can be concluded that the farther from the feeder substation is connected the Statcom, the bigger is going to be the effect of the Statcom on the amplitude of the voltage at its connection point.

To validate this, the selected scenario has been simulated with a STATCOM of 1MVAR installed at CT4 (blue) and compared with the installation of the same STATCOM at CT8 (black). The voltage profile of the two simulations can be seen at Fig 15. It can be seen that the STATCOM installed at CT8 can maintain the voltage along the line in the permissible range, however the STATCOM connected al CT4 is not able to maintain the voltage along the line in the permissible range.

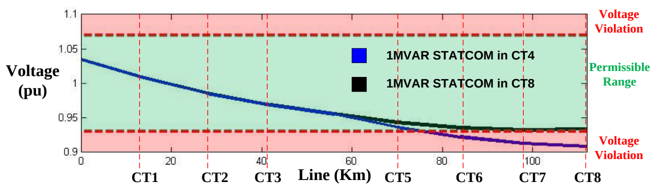


Fig 15.Voltage profile of the selected scenario with OLTC and STATCOM

As it can be seen in Fig 15, the optimal placement of the STATCOM is essential to take advantage of it. Moreover the response of a STATCOM is faster than the response of a SVR, so in long lines with huge variability of power consumption, in which the SVR have to change the tap several times along a day (decreasing its life), it can be a reliable solution.

4. Voltage control in rural distribution networks with penetration of distributed generation

A. Distributed Generation

Due to the increase of the renewable generation connected to the distribution networks [11], the DNOs face several problems because the distribution network actually is designed for unidirectional power flow (architecture, protections ...). Moreover this renewable energy sources cannot be controlled as an ordinary generator and the voltage control is more complicated due to the uncertainty of this kind of generation [4, 12-18].

B. Scenario of Voltage Control with Distributed Generation

The previous scenario has been slightly modified in order to analyze the voltage control with distributed generation. As it can be seen in Fig 16, a photovoltaic power station of 1MW has been installed in CT4 and a wind farm of 1.5MW in CT8. This means a 25% of penetration of renewable generation, based on the power of the header transformer (the limit is established at the 50%).

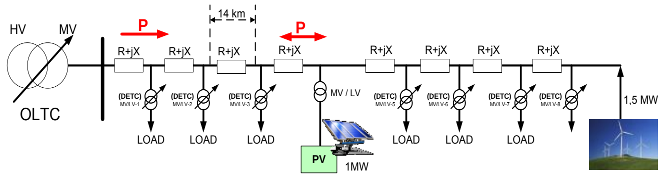


Fig 16. Selected scenario with distributed generation (DG)

The generation profiles presented in Fig 17 and Fig 18, are based on real values obtained from experimental data, where active power is the red line and the reactive power is the green line. In order to have fast power variations, the used PV data is from a clear day with many clouds passing by, and the wind generation data is from a two-bladed wind turbine in very variable wind day. It can be seen that the wind generation presents a fast changing power generation, while the variation of the power generated by the photovoltaic system is slower. The reactive power of the wind power generation is not controlled while the reactive power of the photovoltaic generation is zero.

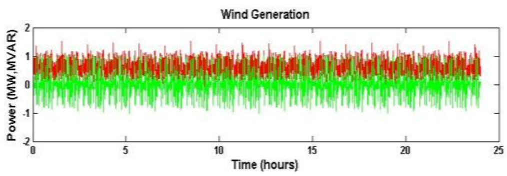


Fig 17. Wind Generation profile

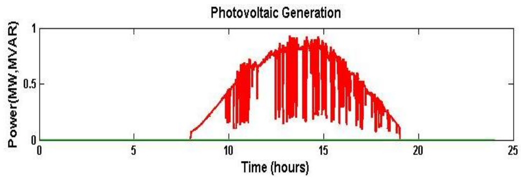


Fig 18. Photovoltaic generation profile

The load profiles that have been selected are typical profiles of a work day, Fig 19, where the active power consumption is shown in red color and the reactive power consumption is shown in green color.

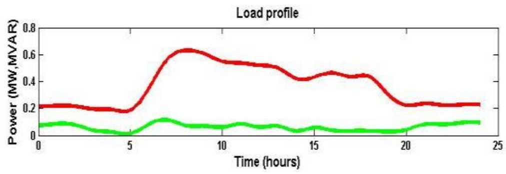


Fig 19. Load profile

Fig 20 shows the evolution of the voltage level at CT8, applying these power profiles to the scenario presented in Fig. 16.

As it can be seen in Fig 20, the voltage of CT8 violates the lower limit of the voltage in the moments of maximum consumption.

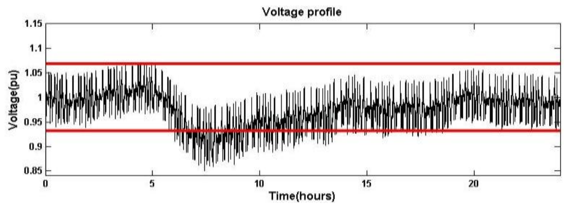


Fig 20. Voltage profile (CT8) of the scenario of Fig 16

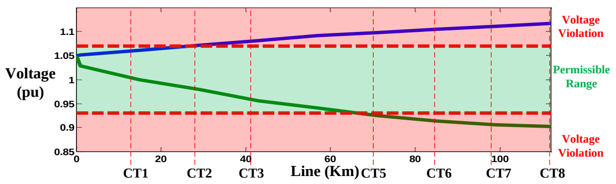


Fig 21. Voltage profile of CT8 and the state of the STATCOM

Fig 21 shows the voltage level along the line at the maximum consumption (green) and at the maximum generation (blue) moments, and in both moments the voltage level of CT8 has the bigger deviation analyzing the established limits.

C. Voltage control with SVR in scenario with (DG)

In order to improve the performance of the previous example, a SVR with LTC control is introduced as shown in Fig 22. This SVR is controlled by a LTC control with direct measure of CT8 voltage. The control of the CT8 node has been selected because this node has the biggest voltage divergences as shown in the previous section. Fig 23 shows the voltage level of the CT8 and the position of the tap changer of the SVR.

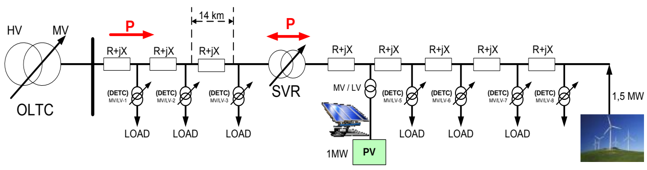


Fig 22. Selected scenario with OLTC, SVR and (DG)

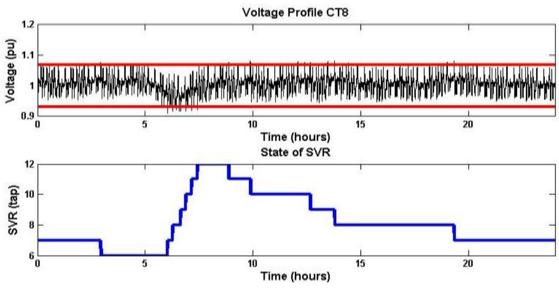


Fig 23. Voltage profile of CT8 and the state of the SVR

As it can be seen in Fig 23, compared to Fig 20 it is clear that the SVR helps to maintain the voltage level between the established limits, but due to the slow dynamic response of the LTC controller there are some moments that this voltage limits are violated. Moreover, it should be noted that the fast power generation variations generate a high number of tap changes in the SVR, reducing the lifetime of the device.

Therefore it can be concluded that the SVR solution for the voltage control of distribution networks with high penetration of renewable generation sources is not the most suitable. In order to improve this voltage control, another solution can be the installation of a STATCOM device. As mentioned before these Statcom devices have faster dynamic response than the SVR.

D. Voltage control with STATCOM and DG

As shown in section 3, the most appropriate placement for a statcom device in a rural distribution network is at the end of the line as shown in Fig 24. The power rating of the statcom is calculated using the equations (6), (7), and (8) and a 1.3MVAR is used in the simulated scenario in order to maintain the voltage level of CT8 within limits.

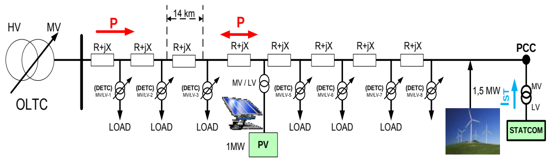


Fig 24. Selected scenario with OLTC, STATCOM and DG

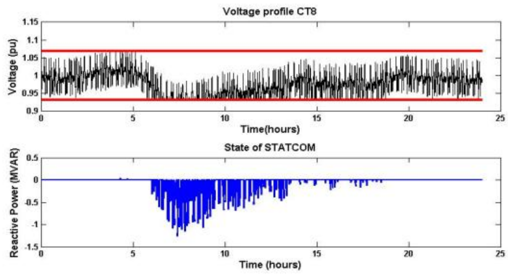


Fig 25. Voltage profile of CT8 and Q-STATCOM

It can be seen that the STATCOM is able to maintain the voltage of the line within the established voltage limits and the dynamic response of the voltage control is better than with the SVR. In conclusion, technically this solution is better than the SVR solution because the voltage always is within the established limits.

E. Voltage control with SVR, STATCOM and DG

The solution proposed in this paper is to use a hybrid solution, which consists of the installation of a 500KVAR STATCOM at CT8 with the SVR installed downstream CT3, as seen in the Fig 26. This hybrid solution takes the advantage of the fast dynamic response of the Statcom, allowing a fast voltage level control and minimizing the tap changes of the SVR. And the presence of the SVR permits to minimize the size of the Statcom connected to the system.

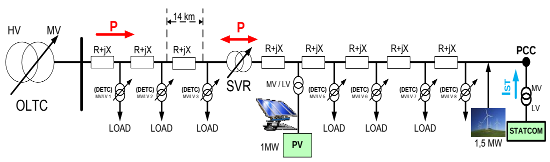


Fig 26. Selected scenario with OLTC, STATCOM, SVR and DG

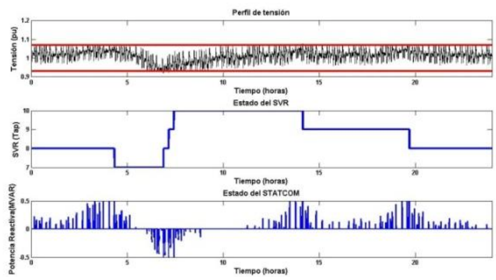


Fig 27. Voltage profile of CT8, state of SVR and Q-STATCOM

The proposed control strategy is based on the minimization of the tap changes of the SVR due to the variation of the load and the generation. So the voltage is controlled by the reactive power injected by the STATCOM, and when the power of the STATCOM is not enough to maintain the voltage level, a tap change is made in the SVR.

As it can be seen in the Fig 27, the STATCOM tries to maintain the voltage of the line between the established limits and when the STATCOM is close to its limit, the SVR makes a tap change. Comparing the results of the Fig 23 (voltage control through SVR) with the results of Fig 27 (voltage control through SVR and STATCOM), the tap changes has been reduced by 50%, increasing the lifetime of the SVR. Moreover the voltage level never violates the voltage limits, because when the STATCOM is arriving at its limit, the SVR makes a tap change.

So the proposed solution with a relatively small STATCOM has the voltage level under control within the limits all the time, minimizing the tap changes of the SVR and increasing the life of the SVR. The proposed solution improves the voltage control in rural distribution networks incorporating new devices without getting rid of any previous control devices.

5. Conclusions

The article has exposed the voltage control problem in rural overhead distribution lines, based on analytic studies and simulations. It has been shown that the voltage control becomes more difficult in presence of distributed generation in these lines due to the variability of these power sources.

Analyzing all the solutions and results, it can be said that the traditional voltage control elements based on magnetic elements present a poor behavior when very variable renewable generation power sources are placed in rural distribution networks. On the one hand the voltage levels go beyond limits quite frequently due to the slow dynamic response of these devices, and on the other hand the lifetime of these control elements is drastically reduced due to the high number of tap changes that are required with these variable power sources.

It has been shown in the paper that Power Electronics devices improve the voltage control of these distribution lines due to the fast dynamic response of these devices. Also it has been demonstrated that the optimal placing of these power electronic devices is necessary to take all advantage of its potential and to minimize the size of them.

A hybrid solution of traditional control devices like SVRs and Power Electronic devices is proposed in this paper. It has been show that a proper control of the different elements increases the lifetime of already installed magnetic devices, and improves the dynamic response of the voltage control, minimizing the size of the required power electronic device. These solutions based in power electronics are the alternative to the traditional solutions used in Medium Voltage lines as SVRs or capacitor banks, but can be also a complement to traditional solutions improving the voltage control.

4. References

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