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Dynamic Line Rating for Congestion Management in Distribution Network

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Abstract. The growth of the demand because of the electrification of the heating system and the popularization of the use of electric vehicles added to an increase on the renewable energies generation connected to the distribution level, are responsible for an increase in the use of distribution network. This may lead to more congestions at this level that up to the date, are solved with direct switching actions which implies a negative economic impact and consequences for consumers and producers. Congestions can be solved also with market-based demand response which need the system to have flexibility to be applied effectively. On transmission network the usage of dynamic line rating (DLR) is more extended but on the distribution level, it is not common. This paper aims to show the use of DLR to provide flexibility to the distribution network, easing congestion management.

Key words. Dynamic line rating, distribution network, congestion management, flexibility.

1. Introduction

The electrical distribution network has traditionally been designed as the fit-and-forget approach which consists of sizing the grid for a peak load in certain conditions that often only occurs for a few hours per year. In the last years, the increase of renewable energy sources (RES), the extension of the usage of the electric vehicle (EV) and the electrification of heating systems to accelerate the transition to a low-carbon energy system, has supposed the proliferation of distributed energy resources (DERs). The distribution system operators (DSOs) are facing a situation where they have a large amount of DER connected to their network. If the network is not reinforced, the increase of DERs may lead to more congestions in the distribution level [1].

Dynamic Line Rating (DLR) is the use of time-varying capacities for thermally constrained lines. As the lines are built for certain conservative thermal conditions, most of the hours of the year the physical capacity is higher than the one they are constricted to. Since the current flow is limited by the thermal constraints, if these are less demanding, more energy can be transported by the lines. This means that DLR can provide flexibility by offering the possibility of increasing the energy that the lines can carry [2].

2. Congestion in distribution network

The violation of voltage and thermal limits are the cause of congestion on the electric system. Depending on the voltage level where this mishap is occurring, different factors must be considered. In high voltage lines, where the R/X ratio (ratio between the resistance and the reactance of the line) is low, the highest temperature of the conductor, which is determined by the sag limit, is the main cause of congestion [3]. In medium voltage levels where the voltage value is lower, the R/X ratio rises which is reflected on higher losses and an increase on voltage variation [4]. At this level the temperature of the conductor is also a reason for the lines to consider since it happens the same as in the high voltage lines. For the case of low voltage networks, the R/X ratio is higher as the voltage level is lower, what leads to a higher influence of active power in voltage variations [5]. This means that hight active power changes due to DG feed-in can cause voltage deviation [1]. The current that the cables are allowed to transport is limited to the degradation due to the temperature.

This paper focuses on the situations when the system is pushed beyond its physical capacity limits (i.e. beyond the thermal limits of the network components), due to excessive distributed generation (DG) feed-in and when congestions start becoming normal in distribution network. This would mean that some RES may not be able to produce the energy because of a saturation in the network. Something similar can occur in case of excessive demand on the system [1],[6]. This means that if all the power generated in DG is being injected to the system on the distribution network, there may be congestions in the lines. This saturation implies a

limitation on the power transfer capacity to ensure the security of the energy supply [5].
Congestion is a critical issue in more dense networks with large share of DG on them. In addition, the popularization of EV will also increase the burden on the distribution network which will also induce more thermal stress in residential networks, prone to experiencing network congestions [7],[8],[9]. The security of the system has already been endangered by congestion in networks with high penetration of DG [6].

A. Congestion management

Traditionally, congestion management procedures have been done by the transmission system operator (TSO) and have mainly been used on transmission networks. Some technical methods such as outage of congestion lines, reconfiguring feeders, market splitting, transformer tap changers and operation of the flexible AC transmission system (FACTS) are still being used today [10]. However, these techniques are not available on distribution network, where, as it has been explained and showed, congestions are more likely to happen with the growth of DG.
An alternative to deal with congestions in distribution networks, is the reinforcement of those networks. Nevertheless, this imply high costs that are reflected on an increase of the CAPEX (which means less benefits for the investors) for the DSO and higher connection inversions for DG developers. The reinforcement requires time to start being used since it must be installed so it is not a viable short-term solution [1]. However, in some cases, a grid reinforcement may be the best solution to implement efficiently improvements on the network. In [3], it is shown how replacing the conductors of the lines by 'Superconductor Technology' can reduce congestion on the lines.
The way that congestion management in distribution networks is done can be separated in two different mechanisms [11].

1) *Direct switching actions*: This consists of the mitigation of the congestion by the load shedding, and the power curtailment. This mechanism can be done whenever it is required but it implies an economic compensation, and it has negative consequences for the agents involved [11].
2) *Market-based demand response solutions*: Consisting of the management of the flexibility resources that are spread on the distribution network [11]. This flexibility can be found as DERs, however when it is not available, this mechanism is not useful [12].

Both mechanisms require the cooperation of the TSO and the DSO to coordinate how to use the available DERs ensuring the good operation of their underlying system [4].

B. Examples of congestion management

In the regional distribution network in the south of Germany, there was an important share of installed intermittent renewable DG capacity, it represented a large percentage of the peak load. In many places, the DG output of the distribution networks exceeded the local load, and in periods of large RES generation, the distribution network could be seen as a large generator.
To face this situation, the DSO was allowed to curtail generation as of certain capacity in case of congestions in the network thanks to the German renewable law. This RES generation curtailed was compensated with a 95 % of lost income (limited to 1 % of annual income). In case of grid congestion, the non-renewable generation would be the first curtailed by the DSO [1].

In Italy, new penetration of renewable energies at the distribution level became a problem. Only in 2011, 10 GW of photovoltaic (PV) were newly connected to the distribution network. At that moment it was the highest yearly increase in distribution generation connected to the grid in the world. To ratify the proper functioning and avoid congestion in the distribution network, the Insernia project was launched. This project consisted in a model for protection, automation and management of power generation in the distribution network by monitoring different agents involved in DG and the installation of 'Smart Info' devices for customers connected to the low voltage grid. Furthermore, aiming an efficient integration of renewable resources, the project included the installation of a charging station for EVs, a PV power plant and a multi-functional storage system.

3. Congestion management using DLR

The thermal limit of the feeders is given by the ampacity, which is the amount of current that the conductor can transport [13]. In [14] where a DLR algorithm and a software application is presented, it is shown that the ampacity of the conductor varies with the weather conditions and has a dynamic behaviour. As it is shown in Fig. 1. the ampacity is inversely proportional to ambient temperature. This shows an example of how ampacity varies with the weather conditions.

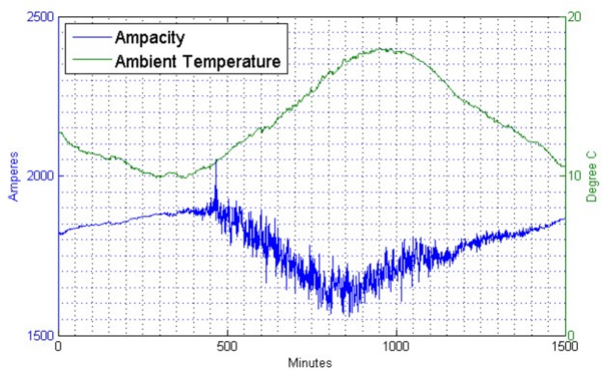

Fig. 1. Ampacity variations due to ambient temperature [14].

Usually, line rating is calculated considering the maximum allowable temperature of the conductor and some predetermined conservative weather conditions from the environment where the line is located. This way of sizing is known as static line rating (SLR) [13]. The maximum allowable temperature oof the conductor does not change but since the weather conditions are changing, the temperature of the conductor does it too. As it can be seen in Fig. 2. the maximum allowable temperature does not vary, unlike the temperature of the conductor.

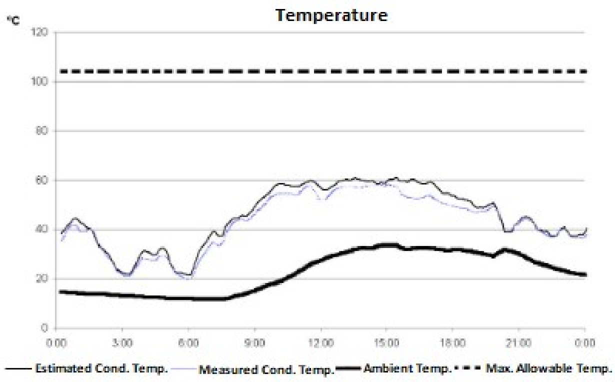

Fig. 2. Conductor real temperature and maximum allowable temperature [15].

As it can be seen, the temperature of the conductor varies with the ambient temperature, as the ampacity. Nevertheless, the maximum allowable temperature is always constant, and it should not be surpassed.

SLR, ensures the proper functioning of the feeders and gives a constant value of power capacity on that line. However, since the physical capacity of the conductor is given by the ampacity and this varies with time, the use of SLR means a significant underutilization of the actual transfer capacity [16],[17]. The maximum carrying capacity of the conductors is constantly changing and determined by the ability to dissipate the heat created by an electric current [18].

Considering the variations of the ampacity, the use of DLR can imply an increase on the operational flexibility and enhance the asset management strategy [2]. In the simulation run in [17], it is shown that only during a 17,6 % of the time, the DLR remains identical to the SLR. This means that for that case and if SLR is used, the capacity of the lines is underutilised the 82,4 % of the time. Many times, the DSO must face scenarios where no more energy can be injected in the lines because they are already at full theorical capacity. The use of SLR is a bottleneck for transfer capacity since it is limiting the amount of energy that can be transported by a limit that are under what the conductor can physically dispatch [18]. In Fig. 3. is shown how a graph comparing the real ampacity, a static forecasted one and a dynamic forecasted one.

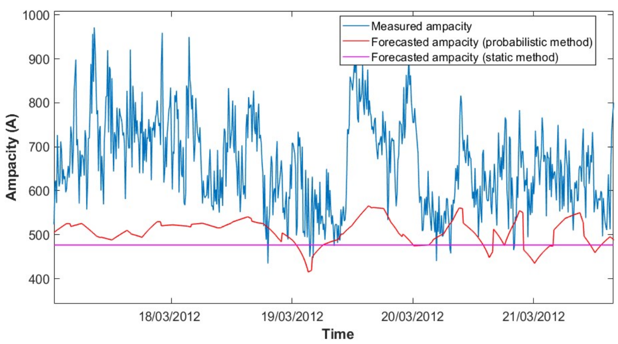

Fig. 3. Comparison of SLR with real and forecasted ampacity [19].

The measured ampacity is higher than the static forecasted one, which would be considered as using SLR. Then with the graph shown in Fig. 3. is proved that the SLR implies an underutilisation of the line.

RES require operation flexibility of the power system to maintain network reliability since RES imply short term variations in power output. DLR can contribute to the system with flexibility by giving a more efficient use to the conductors, preparing the network for higher RES penetration [20]. Furthermore, since the wind has a cooling effect on the lines, more wind power can be integrated into the system if the DLR is implemented. In this case, DLR contributes with more flexibility when the system requires it since more energy is being generated by the wind turbines. It helps to integrate more amount of wind energy into the network.

The low cost of DLR implementation is another factor that works in favour of this tool. The investment consists of the cost of sensors needed to enable DLR [18]. Due to the saving because of congestion cost reduction, it is an economically viable investment. However, there is uncertainty regarding the actual economic beneficiary of DLR since it is hard to define who will benefit from this [2].

Dynamic thermal ratings must be installed on suitable assets and different factors must be taken into account.

A. Implementation of dynamic thermal ratings

In the distribution network, most of the lines that can be found are on medium or low voltage levels. This means that there are overhead lines and buried cables disposed on different topologies such as radial or ring. The implementation of dynamic thermal ratings will be different for each kind of line [21].

The exposure to the environment, makes overhead lines the ones that experience the most temperature variations. These lines are constrained by the maximum temperature at which the conductor expands until the sag or clearance limit [2]. The main factors that have an impact on the heat exchanging are the ambient temperature, the solar radiation and the wind speed and direction being the air the one with the highest influence [21].

The effect of dynamic thermal ratings must be taken into account in buried cables too. The expected life of a conductor is designed to operate at continuous rated temperature under constant and prescribed conditions. Therefore, the thermal limits for underground lines are related to accelerated aging and even physical damage [2],[22]. To avoid overheating the cable insulation, some invariable factors such as the cable construction and installation data and the sheath bonding method must be considered. Other factors such as the soil thermal properties and the ambient temperature that are always varying with the weather, must be taken into account too [23]. The moisture content of the surroundings is one of the fundamental variables that determines the thermal resistivity and specific heat of the soil, which is fundamental to calculate the heat exchange between the cable and the environment [24].

In [21], simulations of dynamic thermal ratings are done in overhead lines, underground cables and power transformers. The results show how overhead lines have the greatest potential for rating exploitation since wind speed and direction are much more variable than soil temperature, soil thermal resistivity and air temperature. This limited variability is seen on the results, while the average rating for underground lines is ranged from 1,00 to 1,06 times the static rating, for overhead lines this range is from 1,70 to 2,53 times the static rating.

B. Application of DLR

Some studies have been made proving the potential that DLR has on the distribution network. Depending on the conditions of the lines, like the emplacement of the installation, the usage of DLR can be more beneficial, although in every study is shown that it is profitable.
Dynamic thermal ratings can be used for increasing the PV hosting capacity (PVHC) on low voltage networks. On the simulation made in [25], it is shown how with the implementation of DLR, the PV capacity increases a 15,40 % in one scenario, 21,60 % on another one and 27,10 % in the last one. Other studies have better forecast like the simulation run in [13] where the installation of DLR suppose an enhance of PVHC up to 40,90 % on average. In [26], it is shown how by the implementation of rephasing, voltage control and DLR, the PVHC can increase a 60,00% on average.
Virtual power plants are gaining popularity, and it is becoming more common to see them on the distribution network. On the study made in [17] of a virtual power plant, the application of DLR obtained an average improvement of the line rating of around 26,60 %. The increase of the power sold achieved with DLR supposed an increase of the benefits of the virtual power plant of 23,00 % in the simulation made in [20].
DLR can be used to optimize the benefits from an electric community. In [27] it is shown how with an efficient programming and the implementation of DLR, the benefit can be increased by almost 1,5 times.
All this examples, are simulations since it has not been implemented into distribution networks yet. However, there are already implemented projects in transmission lines where the results are positive [21].

C. Challenges and issues regarding DLR

First, DLR must be installed in suitable lines, on the ones that will provide more benefits. This means that highly congested lines where the conditions are beneficial for dynamic ratings are suitable but if these conditions are not met, DLR might not be the proper solution [2]. For example, in pure ring topology, the electric lines are oversized and the problems on congestion are seen on the transformers, so DLR is not a good alternative on this topology [7]. For this case, a real-time dynamic thermal rating could be applied to the power transformer allowing it to increase its average rating from 1,06 to 1,10 times the static rating [21].
The DLR implies an additional complexity on power system operation to the system operators. Furthermore, there is necessity to adapt other issues such as protection settings to the new conditions provided by DLR [2]. In addition, DLR introduces a customer interruption risk, due to information and communication technologies failure or lack of accuracy on the modelling and forecasting [28].
There are studies that has combined RES with DLR and other that combines batteries too, but DLR is not popular on distribution lines where congestions will appear more often as the DG increases [2]. The papers of DLR on distribution network are mostly based on simulations and not in real practices.

4. Conclusion

Congestion at distribution level appear because of voltage deviation and thermal limits violations. DLR can suppose a congestion reduction, since it reduces the underutilisation rate of the lines. This, imply a reduction in the costs due to less need of generator re-dispatching, load shedding and power curtailment. It has not an expensive implementation and it should be considered for congestion management. However, dynamic thermal ratings do not solve the congestion due to voltage variations.
It is proved that DLR can improve the injection of DER in the grid. Its usage in wind farms is more extended because of the clear correlation between the higher production of wind turbines and the higher heat exchange of the lines with the environment due to high wind speed. The higher restrictions in the conductors of PV power plants, implies that during a lot of time, the lines are working under their physical limits. This underutilisation can be erased by the application of DLR so it should be taken in consideration in PV plants to increase renewable energy injection.
The use of DLR in the distribution network is limited to suitable lines where its implementation has a beneficial effect contributing with flexibility to the system operator. The combination of DLR with other assets that can improve flexibility such as batteries could bring to the DSO and the TSO more facilities for an efficient congestion management.

In future works it is expected to apply DLR to a real PV power plant and analyse the results. Also determine the efficient way of the application of DLR in distribution lines and study the possibilities of the use of dynamic thermal ratings on underground cables.

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