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Benefits of Dynamic Line Rating on System Operation

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***Abstract*—This paper explores the benefits that ampacity dynamic line ratings (DLR) can offer to obtain a higher penetration of wind power generation in the grid. This paper presents an analysis of real examples where monitoring systems are achieving real benefits when operating the network. Monitoring systems not only provide economic benefits, but can also provide information for ampacity predictions. These predictions can help to plan the dispatch of energy in the electricity market, always taking into account the risk that such predictions may not be fulfilled. The case studies demonstrate the economic benefits and increased wind generation on the grid from the use of DLR on a 24-bus network. It is analyzed which line would obtain a greater benefit from the installation of the DLR, and considering the market prices of the fuel, the economic differences are analyzed by using static ampacity limits and using the dynamic limits obtained based on ampacity predictions.**

Keywords—Dynamic line rating, forecasting ampacity, wind generation.

I. INTRODUCTION

The increase in renewable generation, including wind and solar generation, presents a challenge for the operation of the electricity system due to the variability and unpredictability of the renewable resource. Transmission lines are congested at critical points in the grids and wind farms are forced to be unable to produce at their maximum capacity. Existing power lines are not capable of transporting all the production that wind farms can offer at times of peak wind resource [1].

One solution to increase transmission capacity is the installation of new power lines, however, this solution is very costly. Currently, different methods are proposed to solve congestions. In [2] different points of view for congestion management are proposed. Part of the analysis is based on managing congestion in real time, different studies have shown in certain cases, that the use of real-time system data increases the effectiveness of the network.

Another solution to this problem would be to consider the use of the dynamic ampacity limit on the lines. Overhead transmission lines are operated by static current limits, which in turn are very conservative, leading to situations where the lines work at a lower capacity than they could work. This is due to the influence that meteorological factors have on the temperature of the conductors. The temperature of the conductors is especially related to meteorological conditions such as ambient temperature, solar radiation and wind speed. The influence that the wind has on the cooling of the lines makes this solution particularly interesting in relation to wind energy. The information obtained by monitoring systems, combined with information from meteorological stations, serves to obtain real data on the line temperature and on its real transport capacity [3]. However, energy dispatch planning is done in advance and therefore it would be very convenient to have real line ampacity information hours or even days in advance [4].

In order to analyze the benefits in economics terms and on the increasing penetration of wind power into the system, this article summarizes real applications where dynamic line rating is used. These kind of devices are already making a contribution to the grid. To quantify the benefits that dynamic limits can have over static limits a simulation has been carried out on the IEEE 24-bus system. Not only the benefit of having the information in real time is analyzed, but also the influence of being able to make predictions with data obtained in real time.

II. THERMAL LINE RATINGS

The temperature of a conductor will depend on the charging current, the electrical characteristics of the conductor and atmospheric parameters such as wind and sun. The consequences of exceeding the conductor's maximum temperature are discussed in [5]. If the line temperature exceeds the maximum temperature by more than 10ºC, it can cause injury to people in the nearby perimeter and electrical discharge to distribution lines or buildings below these lines. It is very important to always keep the temperature of the line under control, and never exceed the safety limits. Using real-time monitoring and control systems, with the information provided by weather stations and other devices that monitor the conductor's position and stress, it is possible to calculate the conductor's temperature in real time.

A. *Static Line Rating*

The Static Line Rating (SLR) considers unfavorable conditions for the carrying capacity of the lines. To estimate these ampacity limits, estimates of temperature, wind speed and direction, as well as solar radiation for different times of the year, are usually taken in account. The SLR is calculated with a bare conductor thermal equilibrium model, using conservative climatic conditions e.g. low perpendicular wind speed (approximately 0.61 m/s), near maximum seasonal air temperature (35°C or more in summer) and maximum solar radiation (1000 W/m^2) as described in CIGRE Technical Guide 299 [6].

It is important to consider that the assumed climatic conditions depend on the region and the risk tolerance of the emergency service companies. It is considered a conservative method because many hours of the day these unfavorable conditions do not occur.

In addition, depending on the regional climate, the static ampacity values may be recalculated for each season, instead of remaining constant throughout the year, typically the values are divided between summer and winter. Seasonal static limits are widely used since they apply to all lines in the area or region and no physical modification of the lines is required. In this way, it is possible to increase the limit in winter, because temperatures are usually lower.

B. *Dynamic Line Rating*

The dynamic line rating (DLR) calculates the maximum capacity that a conductor is capable of carrying based on the environmental conditions and temperature of the conductors in real time. Dynamic limits are established based on information obtained from monitoring systems installed on the lines and information provided by the weather stations closest to the lines. This information can be received in real time, or can be predicted with different time ranges. The calculated dynamic limits can be used at different points in the power system. The predictions can help to operate the network in a better way [7], but it is always necessary to have a real time monitoring system to ensure that the maximum allowable temperature of the conductors is not exceeded.

Dynamic ampacity calculation can be classified into two main categories [7]:

- Dynamic Line Ratings with Ambient-Adjusted (DLR-AA), in which ambient temperature variations are taken into account while all other meteorological variables are considered constant.
- Dynamic Line Ratings with Real-Time Monitoring (DLR-RTM), in which the variations of all meteorological variables are considered.

DLR-RTM, as it uses real environmental data monitored continuously, allows for greater accuracy and knowledge about the real ampacity of the line. As a disadvantage, these data can only be used in real time or posteriori, they cannot be used in the previous phases of the energy dispatch, such as the previous day-head electricity market. However, knowing historical values of the real line ampacity and environmental conditions means that much more precise predictions can be made. DLR-RTM can be used to make ampacity predictions that can be used for the energy dispatch that takes place in the intraday markets, where energy dispatches are redistributed due to the lack of energy in necessary adjustments caused by technical restrictions of the system. These restrictions may be caused by network congestion or by problems in the generation plants that had sold their energy in the previous day's daily market. Therefore, knowledge of the real ampacity of these markets could be applied to allow a more optimal energy distribution and a greater incorporation of renewable energies in case they are available.

1) *The use of DLR in ampacity forecasting*

The main advantage of dynamic ampacity prediction is the possibility of knowing the predicted ampacity data hours or days before the energy dispatch. In a market system in which most of the energy is managed the day before dispatch, knowing in detail the transport capacity that will exist in the network is very important. It is common that, due to technical congestions, power plants with generation capacity and with their energy traded, are not able to dispatch this electricity. The information provided by different monitoring devices can be used not only at the time of operating the power grid, but can also serve to make ampacity predictions that can be used in the phases of energy market and planning [8]. Depending on the time horizon over which forecasts are made, these forecasts are used for different purposes. Short-term forecasts, whose timescales are less than six hours, are usually more useful for contingency management. Longer-term forecasts, whose time horizon exceeds twenty-four hours, are more applicable for energy dispatch and electricity supply in the day-ahead market.

The problem of forecasting ampacity using information from resources as variable as the sun or the wind makes it necessary to assume the possibility of making errors in such predictions. It is important to assess the risk of error that can be taken to find the most optimal solution between the benefit obtained and the cost that such errors may suppose. In [9] a study on the benefits of DLR for different levels of uncertainty in the predictions is presented.

2) Benefits of DLR

The use of DLR can allow significant increases in the admissible current in a power line. In this way, many potential benefits can be obtained, which can be summarized as follows:

- Increased integration of renewable energies, in particular wind energy. Due to the high relationship between a higher wind capacity and a higher cooling of the lines.
- Cost reduction by not needing to install new lines, to increase the capacity of the lines.
- Reduction of the cost of electricity production dispatch.
- Increased reliability of the power grid.

a) Economic benefits

Installed renewable capacity is expected to increase worldwide, especially wind power. The increase in capacity brings with it a need for increased transmission capacity on power system lines. The carrying capacity of the lines can be increased in different ways, with improvements to the existing structures in the system, the implementation of different types of conductors with higher capacity or even the installation of new lines. These types of changes and improvements in order to increase the carrying capacity require a large investment. Therefore, it is important to consider that an increase in the capacity of existing lines by using DLR means not having to carry out the investment in new lines.

Congestions are defined as situations in which the lines are unable to carry, due to technical restrictions, the required load during periods of high demand [10]. In the event that the technical restrictions of the network are reduced, the costs produced by these restrictions are reduced, as well as the capacity payments, since it is not necessary to oversize the generation systems. Through the use of DLR, a reduction in the number of hours of congested lines has been observed. This reduces the need to build new lines or extend existing lines.

In order to analyze the economic benefits that a monitoring system can bring, the cost reduction resulting from the introduction of cheaper generation in the market is taken into account. In this way it is possible to increase the capacity of the lines at times with a lot of wind, taking advantage of the power of the wind in cooling the conductor [11].

b) Penetration of renewable energy

There is an important relationship between wind generation and the dynamic ampacity of the lines. The application of the DLR on lines connecting with wind farms is very effective because in conditions of high wind generation, the strong wind guarantees a very good cooling effect on the conductor. So, there is a certain complementarity between wind power generation and DLR. By using SLR in the lines, technical restrictions must be applied in the wind installations due to the congestions that occur in the output lines of these parks, because these lines do not have enough capacity to transport all the possible production. In this way the wind potential is not fully exploited and to complete the necessary production, other more expensive and more harmful to the environment generators are put into operation.

The possible increase of wind installations on the lines is analyzed in [12]. Thanks to the increase of capacity on the lines at times when the wind potential is higher, using DLR it would be possible to install between 20% and 50% more wind energy on the power grids. This increase in the integration of wind energy is important in the electricity system because it reduces the total system dispatch price. By increasing wind power generation, the use of environmentally harmful power plants is reduced, which is a very important factor considering climate change and all the environmental problems related to pollution.

3) Real DLR applications

A review of the different monitoring systems used in different countries is carried out in [13]. The information reflects the different types of devices used in transmission lines. An increasing number of power lines are installing monitoring systems with the intention of using this information for a more optimal management and operation of the network [5].

The following is a brief summary of some of the current DLR installations and the benefit that its implementation has provided.

a) ELIA Belgium experience

The Belgian TSO, Elia, has been one of the pioneers in installing DLR technology on its lines. In 2008, in collaboration with Ampacimon, Elia tested a DLR system on a 380 kV line in Belgium, and since then has increased the use of this technology [14]. Ampacimon has become a technology used in different processes of the network operation, achieving a reduction of the redispatch costs. It is taken into account that the use of the dynamic thermal limit poses a risk in the operation. The Ampacimon technology use small modules that measure continuously the line sag and this allows to calculate the maximum permanent flows that the line can support. This information is used in real time and for forecasts with different time horizons. The real time ampacity gives the permanent maximum ampacity of the line, this amapcity is accurate and refreshed every 5 minutes. However, the ampacity values is too volatile to be used in real-time grid operation. The 1h forecast, gives the maximun ampacity of the line wich can be used with sufficient certainly for the next hour. This amapcity is more stable and is the ampacity used in real-time by Elia in the grid security calculations. Elia also uses forecasts with a longer time horizon, this forecast horizon gives an estimation on the amapcity of a line for the coming 60 hours. This forecast makes uses of weather forecasts and the historical information about weather conditions and measured line-sagging, it is refreshed every 6 hours, using a new weather forecasts [14].

Based on the analysis in [14], the results show that using 48h forecast, during 90% of the time the capacity of the lines increases by more than 10%. ELIA, in agreement with the Belgian regulator, have pre-defined acceptable increase in risk. Consequently, the 48-h forecast rating has been capped to 105% of SLR during peak hours and 109% of SLR during off-peak hours. However, up to 130% of SLR can be used for 1h-forecasted and real-time rating.

b) Terna Italy experience

Terna, the Italian TSO, has searched for an approach to ensure good system accuracy and contain application costs by developing a thermo-mechanical model that estimates the main conductor parameters (sag, temperature, stress) on each section of the line using detailed short-term weather forecasts [15].

Monitoring systems have been installed on the most critical sections in terms of distance to obstacles. Currently, Terna has already installed more than 90 monitoring systems and more than 20 connections are already in operation with DLR, with some more in the activation phase. Before starting a new DLR implementation, Terna performs an in-depth analysis of the line's status [15]. These checks are periodically repeated more frequently than on other lines where DLR has not been installed. The information obtained in these years of implementation has confirmed that the aging of the lines is similar, which leads to the conclusion that equipping them with DLR does not make the lines age faster or more quickly. Several 150 kV lines, in some cases subject to local congestion in high wind conditions, have been equipped with DTR systems. Calculated dynamic limits are almost always higher than seasonal static ones; about 98% of cases in summer, 92% of cases in winter. Moreover, the few cases in which the dynamic limit is lower are not relevant for operation because they almost always occur in accordance with low wind conditions.

c) Viesgo Spanish experience

The Spanish distribution system operator Viesgo has implemented a DLR technology in several of its lines [16]. In 2012 they placed a meteorological system on seven lines and started the design of a steady state algorithm. In the following years they doubled their monitoring systems on the lines and implemented innovations to improve the initial algorithm. Since 2018 all 132 kV lines operated by Viesgo are dynamically managed. Based on the results analyzed in [16], an extra energy of 70.9 GWh was managed considering a scenario of 80% of the static limit, the system was operated dynamically for 171 days. In the other scenario, operating the network considering 100% of the static limit, it is observed that an extra energy of 27 GWh is operated for 81 days. The increase in ampacity ranges was from 21% as a minimum to 114% as a maximum, compared to the static limit. These values indicate that the system operator achieves extra operating flexibility by using the dynamic limits and in turn reduces restrictions on wind generation. According to the yearly medium pool prince, the additional energy transmitted was worth 1.4 M€ with respect to operation at 100% of the static rate, and 3.5 M€ with respect to operation at 80% of the static rate. The use of DLR reduced the emissions by up 7800 tCO_2 with respect to operation at 100% of the static rate, anb by up 2300 tCO_2 with respect to operation at 80% of the static rate.

III. SIMULATION CASE

A. Simulation data

Through simulations, an analysis of the benefit of using DLR and ampacity predictions in the IEEE 24 bus system has been carried out. This network is formed by 24 bus, 10 power generators and 22 lines (Figure 1). The original system has been modified to include wind generation in order to analyze the influence that DLR has in relation to wind power generation. The simulations have been simulated with PowerFactory-DIgSILENT program.

1) IEEE 24-bus system

The different types of plants in the system are gas plants (G1, G2, G7 and G16), one hydroelectric power plant (G13), two coal plants (G15 and G23) and finally three wind power plants (G18, G21 and G22). Plant costs have been defined based on the type of plant technology. Prices have been simplified, since market prices change continuously and are closely related to the current price of fuel (Table I).

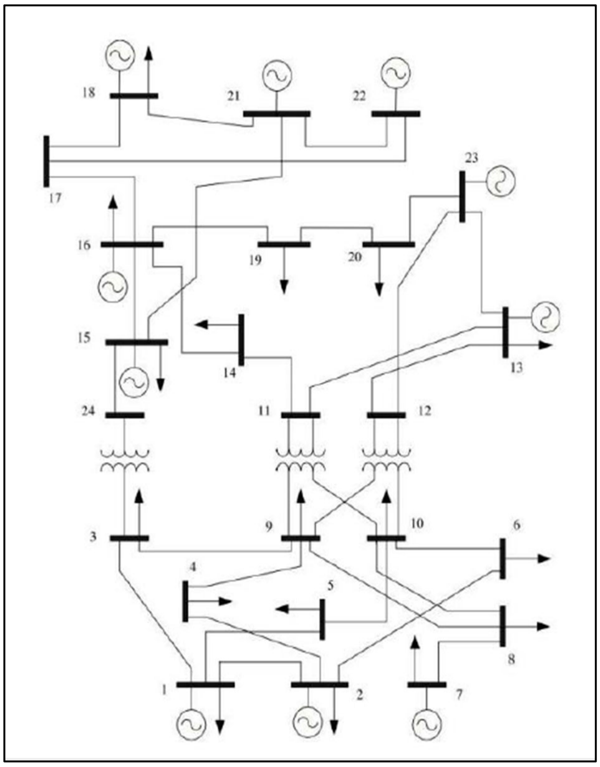

Fig. 1. IEEE 24-bus system

TABLE I. GENERATION COSTS

	Minimum cost $/MWh	Maximum cost $/MWh	Average cost $/MWh
Wind plant	0.00	0.00	0.00
Hydro plant	25.00	40.00	32.50
Gas-fired plant	55.00	75.00	65.00
Coal-fired plant	80.00	95.00	87.50

The ampacity data used in the simulation corresponds to data obtained from [17]. The real data used have been taken from the meteorological station and combined with weather forecasts of the area, carried out by the state meteorological agency with different time horizons. For the prediction of line ampacity, a probabilistic proposition is carried out, which is performed by taking as input data measured on the line, in time horizons between 30 minutes and 24 hours. From these data, linear regression models are used, which allow to obtain from these input data, a probabilistic model of an output variable. In this case, this methodology is used to predict the ampacity of the line with a given level of risk. This risk is the percentage chance of exceeding the maximum allowable temperature. Higher risk levels imply a higher transport capacity of the network, which means a higher utilization of the network, at the cost of reducing the safety of the line. The predicted ampacity was obtained by probabilistic prediction using linear regression models with different time horizons. These linear regression models are used to obtain values from input parameters such as weather data from the previous day or historical weather data.

2) Analyzed scenarios

A small analysis has been made on the effect of applying DLR on the different lines with congestion in the system, in order to know the line where the implementation of this technology would have more impact. The line linking nodes 16-17 is where a DLR system installation would have the most impact on this system, because this line exports energy from a wind generation area.

For the simulations carried out, the values of static ampacity, real or measured ampacity, and predicted ampacity were used with a 2.5% risk, and with a 10% risk level. It was decided to use these data as the most representative, since they allow an adequate balance between risk and network utilization. In the search for this balance, the values of 25% and 50% have been discarded due to the high risk to safety, as well as the values of 1% and 0.5% due to the low influence that this level of risk would have on the ampacity. The system analysis will be done during an hour of high demand and high wind resource.

B. Results obtained

In the simulation, power dispatch data is obtained, as well as the distribution of generation among different types of generators. The results allow compare the cost of energy production with different ampacity limits on the line. By comparing the CO_2 emissions predicted in the different scenarios analyzed, it is possible to relate the implementation of DLR systems to the reduction of pollution.

1) Renewable energy penetration

The variation of the penetration of wind energy in the grid, based on the different ampacity values used, reflects that the use of DLR allows a greater integration of this type of generation in the grid. It is observed that when such ampacity predictions are made with a risk level of 2.5%, the growth of wind generation is 23.4%, increasing to 33.51% when the risk level used is 10%. The real ampacity values would provide up to 39.66% of wind generation growth in the system.

2) Economic benefit

The production costs change according to the ampacity values used. Comparing the dispatch cost required by the system, there is a clear cost reduction in the case of using the ampacity predicted by the DLR systems. When the ampacity used is that calculated from predictions with a risk level of 10%, the system has a cost reduction of 20.25%, for ampacity values obtained from predictions with a risk level of 2.5% the system cost reduction is 14.80%.

3) Reduction of the CO_2 emisions

At the time of analyzing the emissions when applying the DLR, the emissions per MWh have been considered according to the estimates provided by REE. Based on the generation technology used in each scenario, an approximate calculation of the emissions that this generation would entail has been made. For this analysis it will be considered that renewable energies have a zero CO_2 emission, not taking into account the emissions that may occur during the manufacturing processes of such generation. The use of the predicted ampacity with a 10% risk level implies a 21.8% reduction in CO_2 emissions, in the case of using the predicted ampacity with a risk level of 2.5% implies a 15.01% reduction in emissions.

IV. CONCLUSIONS

The use of dynamic ampacity limits is beneficial for the power grid in the different factors analyzed. On the one hand, a higher penetration of renewable energies is achieved, reducing the technical restrictions suffered by wind energy. Through this growth in the use of renewable energies instead of conventional power plants, which in turn are more polluting, there is a decrease in CO_2 emissions. As it has been demonstrated by simulations, the use of ampacity obtained by predictions made on the basis of real data, means a cost reduction in the dispatch of energy. In case of using higher risk levels the benefit obtained will be higher.

However, it should be noted that in carrying out these simulations the dispatch and generation prices have been simplified, considering only the costs of power generation. For a more precise and detailed study it would be necessary to take into account other aspects of the market, such as the reserves to be used in case of failure of the forecasts and the different penalties that generation may have if it is not able to produce what it has offered in the market.

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