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Operational Analysis of Dynamic Line Ratings

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Abstract. Overhead line is an important asset for power industries. Rising demand in electricity, environmental concerns and cheaper electricity prices are some important factors behind operating the lines at their maximum potential. Replacing overhead lines and/or constructing new lines are not only expensive but also at the same time raise environmental concerns. However, rating overhead lines based on their natural capacity besides being cost effective is a technically feasible solution. In this project, the operational analysis of dynamic line ratings (DLR) is conducted to analyze potential of DLR when practically implemented across overhead line in a sub transmission network. It further guides system operators in fully utilizing the line capacity to its maximum potential. The project also investigates the impact of Flexible AC Transmission System (FACTS) device in the presence of DLR technique to control power flow from wind generators for stabilized and controlled transfer of electricity.

1. INTRODUCTION

In times of facing economic and environmental challenges, power industries are looking towards effective solutions in making power components more effective and fully usable to save money and protect the environment. Rating overhead lines based on their natural capacity makes them an affordable solution for power industries to adopt. Dynamic line rating (DLR) is not only based on real-time weather and line loading but also is dependent on line sag and its tension. Previous research on DLR has mainly focused on either basing the line rating on real-time weather scenarios or line sag and/or tension [1]. In this paper both approaches are implemented together.

High wind speed and low ambient temperature are two main weather factors in line capacity enhancement. In New Zealand, due to windy summers and cold winters, the DLR technique is quite beneficial for transmission system operators in enhancing the line capacity. Additionally, the role of FACTS devices in presence of DLR improves system's stability besides making active and reactive power flows regulated and controlled. In this project, thyristor controlled series capacitor (TCSC) was employed to control and regulate the active and reactive power flows based on bus terminal voltages.

The advantages of employing FACTS device with DLR involve the followings: 1) Regulating the AC power through voltage control; 2) Transmitting additional power at controlled voltage; 3) Maintaining the small-signal stability by damping power oscillations; 4) Transmitting excess power with no violation in line-sag limit. The advantage of DLR technique also involves distribution and transmission system operators to transfer additional power across existing network without investing on upgrading or building new lines [1]-[2].

Dynamic rating of overhead lines varies significantly with weather parameters and conductor temperature. The change in conductor temperature further affects the line sag and therefore it needs to be monitored continuously. Besides, due to excess wind energy, wind farms are mostly installed in rural areas with no direct connection with strong grid [3]. Therefore, the only options available are to either build a new line or to up rate the existing overhead lines based on dynamic ratings. However, the environmental concerns, high costs and time required in building new lines (as compared to installing wind farms) and more importantly the association of conductor cooling with the wind power restricts from building the new lines.

Electrical distribution network operators face number of challenges, like increment in distributed generation, load growth and ageing infrastructure. Due to these reasons, the need for developing and implementing those techniques which will allow more efficient asset utilisation has arisen. DLR is mainly used to increase the capacity of overhead conductor in terms of transmitting the maximum electric current besides transferring the electricity during peak load and emergency states [4].

The heat-balance equation working under heat absorption and heat loss decides the conductor rating. For conductor to transmit higher electricity, it is required to dissipate more and absorb less heat energy. The more the heat absorbed by it, the lesser it becomes efficient in transferring the power and vice versa. Similarly, from the reliability perspective, the absorbed heat energy should instantly be radiated to not affecting sag of the line (mid span point). Dynamic line rating calculation is based on type of conductor (mainly its diameter), its real-time loading (i.e. the temperature rise), real-time ambient temperature, real-time wind speed and its direction [5].

Adopting the dynamic thermal line rating technique is considered a challenge for control room operators in case of limited knowledge about monitoring the steady state and post-contingent line loadings [6]. Besides, before implementing the DLR technique in the electricity network, the comparison of results from normal and emergency states is important in terms of helping the control room operators to allow exact wind energy from the wind farms to avoid sag violations and maintaining the system reliability.

Conductor sag however affects operational line ampacity and is mainly dependent on terrains and span length. In New Zealand, due to extensive terrains, the span length of conductor besides ground clearance vary significantly and therefore it is a decisive factor in determining the operational capacity of the line (relatively different from its maximum capacity) [7]. This project develops a technique that determines the operational line ampacity for the power system operator to direct the power flow and loading the line accordingly. However, the challenges associated with operational implementation of dynamic ampacity across overhead conductors are power system security, availability of spinning reserves and dynamic ampacity variations [7]-[9].

DLR helps system operators in knowing the true thermal limit of transmission lines before loading them. By doing so, the delivery of excess power through overhead lines during high demand helps in unnecessary load shedding during contingencies in the network. Consequently, additional power can be transferred economically due to minimal expenditure associated with implementing the DLR in the network. This practice is considered important when considering the demand of transmission open-access rules of operation as it encourages wheeling of power with economic energy transfers [10].

From both the installation cost and energy transfer capacity viewpoints, the DLR approach may be able to offer the greatest potential benefits at minimal cost. In comparison with line re-tensioning technique, the implementation of DLR system can provide 67% gain in energy transfer capacity at 62% of the cost associated with line re-tensioning technique [11]. Moreover, by calculating the hours of potential thermal overload, the DLR approach may allow the overhead line to transfer power up to twice the value of its static rating [3]. The analytical and experimental results show that the DLR technique has the potential to accommodate excess energy in the existing infrastructure, with maintaining the operational security [11].

2. MATHEMATICAL MODELLING

Dynamic ampacity of the overhead conductor depends upon two main factors, i.e. its physical characteristics and the environmental parameters [12], with sub categories such as conductor diameter, conductor temperature, ambient temperature, wind speed, angle between wind speed and conductor, and the solar radiation. Dynamic Line Rating is calculated by taking into account the mathematics behind heat energy absorption and consumption as represented in Equations (1)-(9) [13]. According to heat balance Equation (1),

$$Heat_{GAIN} = Heat_{LOSS} \tag{1}$$

Heat gain is related to heat absorbed by conductor and the solar radiation, i.e.

$$P_{loss} + Q_{solar} = Q_{convection} + Q_{radiation} \tag{2}$$

Furthermore, the absorbed heat depends on the amount of current and the conductor resistivity, i.e.

$$P_{loss} = {I_i}^2 * R_{T_C} \tag{3}$$

Conductor resistivity as shown in Equation (4) is based on difference between low and high conductor resistance as well as on temperature differences, i.e.

$$R_{T_C} = \left[\frac{R_{T_{high}} - R_{T_{low}}}{T_{high} - T_{low}}\right] * \left(T_{C,i} - T_{low}\right) + R_{T_{low}} \tag{4}$$

Solar absorptivity depends on many factors like conductor's projected area (A), absorptivity constant (β_i), global solar radiation (φ) and the effective incidence angle (θ) between conductor and sun's rays, time and day, i.e.

$$Q_{solar} = \beta_i \varphi \sin(\theta) A_{p,i} \tag{5}$$

Heat radiation from the conductor is divided into two types, i.e. high and low. The low heat radiation is related to lower wind speed, mainly lesser than 0.5 m/sec [7], i.e.

$$Q_{FC\_low} = \left[1.01 + 0.0372 \left(\frac{D_i * \sigma * V_W}{\varepsilon}\right)^{0.52}\right] \alpha * K_{angle} * \left(T_{C,i} - T_A\right) \tag{6}$$

Whereas, the higher heat radiation from conductor is dependent on wind speed above 0.5 m/sec [7], i.e.

$$Q_{FC\_high} = \left[0.0119 \left(\frac{D_i * \sigma * V_W}{\varepsilon}\right)^{0.6} * \alpha * K_{angle}\left(T_{C,i} - T_A\right)\right] \tag{7}$$

The higher the difference between conductor and ambient temperatures, the higher it can be loaded.

$$Q_{radiation} = 0.0178 * D_i * \epsilon_i * \left[\left(\frac{T_{C,i}+273}{100}\right)^4 - \left(\frac{T_A+273}{100}\right)^4\right] \tag{8}$$

Overall, the dynamic ampacity of overhead conductor as shown in Equation (9) is increased when difference between heat absorption and heat radiation is reduced with decreased conductor resistance and vice versa.

$$I_i = \sqrt{\frac{(Q_{convection} + Q_{radiation}) - Q_{solar}}{R_{T_C}}} \tag{9}$$

Both span and line length have direct relation with changes in line temperature ($T_f - T_i$), its tension (H_f -H_i), cross-sectional area (A) and the thermal expansion coefficient (σ) as represented in Equations (10) and (11). Considering that, the line sag varies proportionally with line length as represented in

Equation (12).

$$L_2 = L_1 * \left[1 + \sigma * \left(T_f - T_i\right)\right] * (1 + \frac{H_f - H_i}{E * A}) \tag{10}$$

$$new_{sag} = (new_{length})^2 * \frac{per\ unit\ weight}{8 * (new_{tension})} \tag{11}$$

$$\Delta sag = \sqrt{\frac{3 * Span\ length * (Change\ in\ condcutor\ length - Span\ length)}{8}} \tag{12}$$

Equation (13) represents the TCSC response in controlling the active power through the voltage phasor by compensating reactance of the line connected between both wind farms. Moreover, the difference between static and dynamic ampacities as given in Equation (14) results in additional power flow (P_Δ) that otherwise is limited by adopting the worst weather based line ampacity. The network was modelled in power factory with wind generators connected at both end so the overhead line as shown in Fig.1.

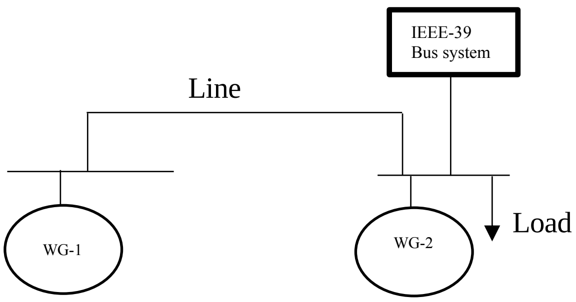

Fig. 1. Single line diagram of the modeled network

Moreover, as represented in Equation (15), the active power from wind generator 1 in Fig.1 is wind dependent so is the line ampacity hence resulting in additional power to be reliably dispatched through the overhead line. Similarly, the active power from wind generator 2 in Equation (16) is transferred through the same overhead line that based on line sag as shown in Equation (11) does not result in line elongation and helps system operators load the line safely.

$$P_{im} = \frac{U_i U_m \sin(\Phi_{im})}{j(X_{TCSC} + X_{line})} \tag{13}$$

$$P_\Delta = \left((I_{DLR} - I_{SLR}) * V_{L-L}\right) \cos(\phi) \tag{14}$$

$$\begin{cases} u_i < u < u_r \rightarrow P_{w,1} = \frac{P_{w,r,1}(u - u_i)}{(u_r - u_i)} \\ P_{w1} = 1.5 * (V_{ds,1} I_{ds,1} + V_{qs,1} I_{qs,1}) \end{cases} \tag{15}$$

$$\begin{cases} u_i < u < u_r \rightarrow P_{w,2} = \frac{P_{w,r,2}(u - u_i)}{(u_r - u_i)} \\ P_{w2} = 1.5 * (V_{ds,2} I_{ds,2} + V_{qs,2} I_{qs,2}) \end{cases} \tag{16}$$

The active power produced from wind generator 1 results in 'I_1' and is directed to pass through the overhead line towards the load center. Similarly, the active power from wind generator 2 resulting in I_2 passes through the same overhead line resulting in the added power flow.

Now,

$$I_1 + I_2 = \frac{(P_{w1} + P_{w2})}{V_{L-L}} \tag{17}$$

$$P_{added} = \sqrt{3} * [(I_{DLR}) - (I_1 + I_2)] * V_{L-L} \tag{18}$$

Similarly, P_{added} in Equation (18) determines the added power flow through conductor as shown in Fig.2.

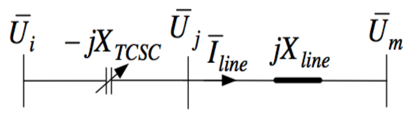

Fig. 2. TCSC steady-state circuit representation

As shown in Fig.2, TCSC controls the power flow through X_{TCSC} that provides controlled I_{line}. Both wind generators in Fig.1 are connected at both terminals of the line, where the line is operated under DLR technique. The modelled grid is considered weak where inconsistent wind speed causes voltage fluctuations at both connected wind generators. TCSC therefore helps in improving the grid stability and avoiding the voltage fluctuations.

3. Simulation and Results

In this project, the operational analysis of conductor ampacity is investigated under sag and voltage limits, where, its voltage limit is set by TCSC as shown in Fig. 1. The modeled network is equipped with two wind power plants and one FACTS device 'TCSC.' The projected overhead conductor moreover connects both wind generators to the load-side and is loaded until it reaches its maximum capacity to find the actual line potential in transferring the maximum generated electricity to the loads as shown in Fig.3.

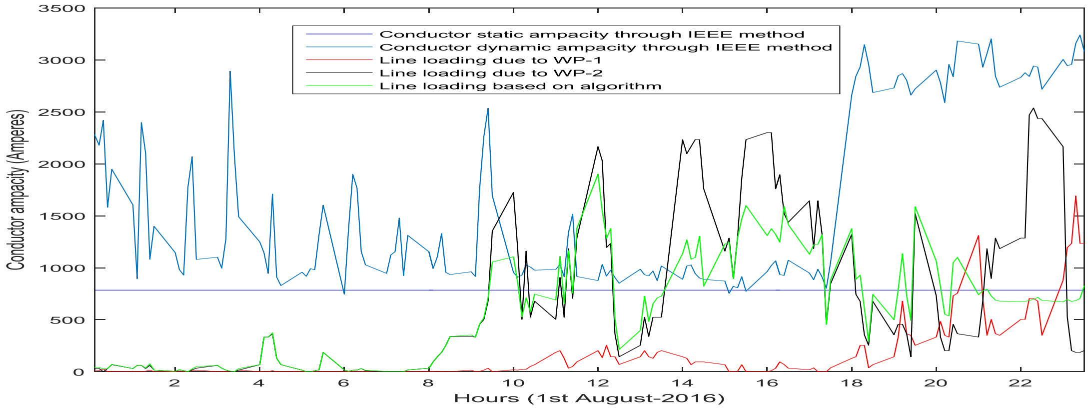

Fig. 3. Conductor ampacity versus line loading

Table I shows line loading and its dynamic ampacity versus wind power generation. Based on the line loading, conductor temperature and line sag are monitored as shown in Table I. The weather parameters were collected for one particular hour in 1st August-2016 at the overhead line location near the area of Nelson in New Zealand. Moreover, based on the sag limit, the overhead conductor is allowed to pass the adjusted power flow from both wind generators simultaneously.

Table I. 1-Hour Line Data (at every 10-minute interval) based on Conductor Loading

Power from WG-1 (MW)	Power from WG-2 (MW)	Loading by algorithm (due to power from both wind generators) (A)	DLR (A)	Conductor temperature (^{0}C)	Conductor sag (m)
15.05	10	169.5	1111	31.4	0.941
1	5	40.6	962	23.3	0.694
1.5	4.5	40.6	821	23.7	0.7
4	0	27.1	800	22.5	0.675
0	4.5	30.45	583	23.9	0.72

The proposed algorithm selects dynamic ampacity if found lower than actual line loading to allow maximum power from wind generators through the line.

4. Conclusion

In this project, the overhead conductor is considered to transfer active power from two wind generators in the presence of FCATS device. The resulting current based on the line power flow is compared with line's static and dynamic ampacities under conductor sag as a constraint. The resulting sag moreover suggests the maximum line loading and the maximum power, the overhead line can transfer in the designed electricity network. In order to achieve the maximum controlled power flow through the overhead conductor, a FACTS device is then connected in series with the line that moreover is observed in reducing the power oscillations when overhead line experienced different power flows due to dynamic ampacity.

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