Analyzing the Output of Bundle-Controlled Line Impedance Modulator (LIM) based Power Control and Line De-icing using MATLAB

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Abstract: Here in this work the analysis were carried out upon the output of a Bundled Controlled Line Impedance Modulator (LIM) based power control and line de-icing of transmission line using MATLAB / Simulink. More specifically, it is based on the implementation of switching modules (SMs) in segments of a transmission-line phase conductor made of bundled sub-conductors. A number of these switching devices must be distributed throughout the power grid and controlled in a coordinated way to manage the power flow.

Keywords: FACTS, LIM, De-icing, Power Control

I. INTRODUCTION

Due to increase in demand, the transmission system becomes more stressed, which in turn, makes the system more vulnerable to voltage instability. Voltage stability has become an increasingly important phenomenon in the operation and planning of the present-day power systems. Voltage collapse is a process in which the appearance of sequential events together with the voltage instability in a large area of system can lead to the case of unacceptable low voltage condition in the network. Increasing load can lead to excessive demand of reactive power and system will show voltage instability. FACTS and DFACTS controllers are used to enhance power system performance. These controllers can reduce electrical distances, modify power flows and absorb or provide reactive power. It increases all types of stability of the system. Ice accumulations on conductors in transmission lines are more common to areas where snow fall is quite an obvious phenomenon. This phenomenon of ice formation can cause severe damage to the transmission line. So, to overcome this problem, de-icing technique is also discussed here.

II. OBJECTIVE

Possibly the most significant issue in terms of grid utilization is that of active power flow control. Utility customers purchase real power, megawatts and MW-Hrs, and not voltage or reactive power. Thus, control of how and where real power flows on the network is of critical importance, and this is done by using D-FACT device. Most of the countries in the world use ac transmission as the main transmission system. So, it is essential to melt the ice for the stability of the power grid and here this is done using DFACT device. The Bundle-Controlled Line Impedance Modulator (LIM) is a distributed FACTS device that has the capability of increasing the impedance of high-voltage transmission lines has been explained here.

III. METHODOLOGY

A model of Transmission line is developed in MATLAB / SIMULINK. Then power flow control and de-icing of a transmission line is implemented using the Line Impedance Modulator (LIM) technology. More specifically, it is based on the implementation of switching modules (SMs) in segments of a transmission-line phase conductor made of bundled sub-conductors. A number of these switching devices must be distributed throughout the power grid and controlled in a coordinated way to manage the power flow. The system and method can, in principle, be used for modifying the power flow through an electric grid in static or dynamic mode.
In power engineering, the power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system. A power-flow study usually uses simplified notations such as a one-line diagram and per-unit system, and focuses on various aspects of AC power parameters, such as voltages, voltage angles, real power and reactive power. Power-flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power-flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. The power transmitted over an AC transmission line is a function of the line impedance, the magnitude of sending-end and receiving-end voltages, and the phase angle between these voltages. Traditional techniques of reactive line compensation and step-like voltage adjustment are generally used to alter these parameters to achieve power transmission control. Fixed and mechanically shunt and series reactive compensation are employed to modify the natural impedance characteristics of transmission lines in order to establish the desired effective impedance between the sending and receiving-ends to meet power transmission requirements. Voltage regulating and phase shifting transformers with mechanical tap-changing gears are used to minimize voltage variation and control power flow. These conventional methods provide adequate control under steady-state and slowly changing system conditions, but are largely ineffective in handling dynamic disturbances. An important feature of interconnected AC systems is that power flow control through specific control paths is often quite difficult. This is because power flows in these paths as per Kirchhoff laws: the line parameters, topology of the network, generation and load location determine the value of flows. The power flows are not directly dependent on transmission line ownership, contracts, thermal limits or losses!

The figure given on the right demonstrates a possible scenario wherein there is power flow in interconnecting tie lines of the two areas although each of them are individually self-sufficient. Thus, the tie lines are unnecessarily loaded. This may be a problem if the capacity of the tie lines is limited.
and one actually wishes to transfer power from one area to another. This is because a part of the line capacities is utilized due to the undesired "loop flow". Power Flow control can be achieved by changing effective line parameters by connection of lumped series capacitors.

Series Compensation of lines
This involves changing the effective series reactance of lines by connecting capacitors in series with a line. Reducing line reactance also improves stability of a system (see module 2 for a discussion of large disturbance stability).

![Fig-3 Load flow](image)

**Thyristor Controlled Series Compensator (TCSC).**
Since the amount of loading changes with time, the amount of series compensation may be varied by bypassing (shorting out) these capacitors when not necessary. Normally a capacitor can allow for short duration over-rating for a few seconds. This allows insertion of larger capacitive reactance into a line for a short time in order to improve angular stability. Alternatively, they may be controlled using power electronic controllers. For example, a TCR (discussed in the section on voltage control), may be connected in parallel to the series capacitor and its effective reactance may be controlled by controlling the firing angle delay. This device is called a Thyristor Controlled Series Compensator (TCSC).

![Fig-4 Series Compensator](image)

**V. LINE DE-ICING**
Icing phenomenon on transmission line occurs due to low temperature, freezing rain, and so forth. Ice formation on transmission line is a common natural disaster. Most of the countries of the world like China, southwestern America, North Caucasus in Russia, Japan, Britain, Finland, some part of India is facing problem due to ice formation on transmission line. Serious ice coating will influence the stability and security of power grid operation. So, transmission line de-icing is a major concern issue and should be resolved by different de-icing techniques. There are many methods which are being employed to deice the transmission line like mechanical de-icing, electric melting ice or thermal de-icing, and natural passive de-icing methods and many more.
(1) Mechanical de-icing uses mechanical force to make the ice break and fall off, which mainly contains — ad hoc method and pulley scraping method.
   - Ad hoc is a kind of artificial knock de-icing method; it relies on external force to percussion de-icing,
   - pulley scraping method is to eradicate the ice by artificial pulling the pulley on the line, which is a feasible mechanical de-icing method on transmission lines.

(2) The thermal method of de-icing uses joule heating effect that heats the icing conductor with huge current so that ice melts.

(3) Natural passive de-icing is a method that is based on the environmental elements of wind, gravity, and temperature variation to make the ice drop naturally without additional energy. In spite of these methods, other methods are proposed such as pulse electric heating de-icing, corona discharge de-icing and infrared heating de-icing etc.

A.C. Line De-Icing
Most of the countries in the world use ac transmission as the main transmission system. So, it is essential to melt the ice for the stability of the power grid. The main method described for de-icing the transmission line is described below.

- Short-Circuit De-icing:
  Short-circuit de-icing is one of the most frequent methods which are in practice. During the melting period, short-circuit current needs to be huge enough so that accumulated ice melts, without exceeding the thermal limit of the conductor. According to the different categories of short-circuit faults, there are three categories of de-icing: three-phase short-circuit de-icing, two-phase short-circuit de-icing, and single-phase short-circuit de-icing. These methods can be employed respectively for transmission lines, double overhead ground wires and lighting conductors.

- DC De-icing in AC Lines:
  The development of the dc technology and the design of high current controlled rectifier make the dc de-icing feasible and efficient. The dc de-icing is achieved using direct current and suitable for all kinds of voltage level. This method requires the formation of a closed loop using line conductors or a loop of two transmission lines connected in series. The icing conductor must be isolated at both ends from its normal ac supply. Comparing with ac de-icing, the required power source and de-icing current of dc de-icing are much lower as the capacity of dc de-icing only depends on the dc resistance and the length of the transmission line.

- On-Load De-icing:
  In some condition, some important loads not allowed to be isolated form the network. Short-circuit de-icing requires taking the lines out of service. So, it is necessary to use the on-load de-icing. The basic theory of on-load de-icing makes use of more current on the ice accumulated lines without cutting the lines. Then heating of the selected lines causes the ice to melt. The advantages of on-load de-icing are that the entire loads remain connected to the reduced network, and no additional equipment is added in the melting process. Only the timely switching of lines needs to be considered. There are many ways of on-load de-icing such as power flow de-icing, reactive current de-icing and phase-shifting transformer de-icing.

- Single converter on-load de-Icing:
  When HVDC works in the mode that the power of bipolar flows opposite, the direct voltage of two polar is in the same polarity. Therefore, two lines which outside the ice coating areas are connected to form the mode of single side converter on-load de-icing. By adjusting the position of short-circuit point, the icing conductor can be selected to connect with its relevant side converter to form a de-icing circuit loop. Thus, it is more efficient to de-icing as the power loss between the line outside the short point and other sides converters can be saved largely.

VI. MATLAB SIMULINK MODEL
Model Description

This model shows two generators and a 10,000 MVA equivalent power system interconnected by three 735-kV transmission lines.

- Lines L1 and L2 are conventional 30- and 90-km long transmission lines.
- L3 is a 60-km long line with two switching modules installed at its mid-point. Line L3 with the two-line segments forms a back-to-back LIM.
- Power outputs of generators 1 and 2 are respectively set at 2400 and 2500 MW. Given their respective loads, connected at the 13.8 kV for the sake of simplicity, they each supply 2000 MW to bus B1 and B2 respectively.
- Line L2 being much longer than L3, its normal power flow is only 1573 MW when the LIM's switches are all closed. Power flows on L1 and L3 are 415 and 2404 MW respectively. The impedance control command transmitted to the LIM is produced by a signal generator inside the LIM impedance Control block. The Z cmd signal ramps between 0.5 and 3 s from its minimum value 1.0 (when all four sub-conductors are used) to its maximum value 1.642 pu (when only one sub-conductor per bundle is used). It then varies in steps after t= 4 s. As shown inside the LIM subsystem, a look-up table associates 58 combinations of 24 switch states to the requested impedance command. As explained in, these combinations have been selected to maintain negative- and zero-sequence currents at a level smaller or equal than observed when all switches are closed. The 58 switch combinations used here represent a very small subset of the 33752 switch combinations provided by a pair of BCL segments. Each line segment is represented by a 14-conductor Exact-Pi section.

VII. RESULT

Asarule, onahigh-voltagetransmissionline,severalconductors are usually provided for each line phase to reduce corona losses and the impedance. Within a bundle, yoke plates and spacers hold individual sub-conductors separate from and parallel to each other. The line-impedance modulator can operate with any number of sub-conductors per bundle but, for the purposes of this thesis, we will restrict our discussion to a 735-kV power transmission line with two sub-conductors per bundle. As shown in
Fig.7.1, the line impedance can be modulated by installing switching modules (SMs) at a number of locations and in all three phases of the line allowing either one, two, or three conductors to be disconnected. One sub-conductor in each bundle is left unswitched at all times.

So, in our model this is connected on L3 line. When we run this model and observe the following sequence of events.

**Scope 1**

- At \( t = 0 \) s, all the LIM’s switches are closed. Power flows in each line are annotated in blue in the example next to each transmission lines.
- At \( t = 0.5 \) s, the impedance signal \( Z_{cmd} \) ramps from 1 to 1.642 pu as shown by the yellow trace. For each values of \( Z_{cmd} \), the look-up table provides the corresponding switch combinations. The switch combinations transmitted to the switching modules are sampled here every 0.1 s. This gives the discretized impedance signal \( Z_{disc} \) (magenta).
- At \( t = 3 \) s, the LIM impedance is maximum. Note that power flows in L2 (magenta) and L3 (blue) are almost equal. Power flows at this point are annotated in red.
- At \( t = 4 \) s, the LIM impedance is set to 1 pu which closes all switches. As a result, power flows in the lines vary abruptly within 1 cycle. This perturbation forces the synchronous generators governors to react and stabilize the power flows back to the initial values prevailing at \( t = 0 \) s.
- At \( t = 5 \) s, the LIM impedance signal returns to 1.642 pu which again induces a power flow perturbation.
- At 6.3 s, the LIM impedance is reduced down to 1 pu in three large steps.

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*Fig.-6 Circuit Diagram for LIM*
**LINE PARAMETERS**
Three bundles of 4 Bersfort ACSR 1355 MCM conductors; two 1/2 inch-diameter steel ground wires. $Y_{\text{tower}}$ and $Y_{\text{min}}$ are the average heights of conductors.

**LINE GEOMETRY:**
- Frequency (Hz): 60.00
- Ground resistivity (ohm.m): 100.000
- Number of phase conductors (bundles): 3
- Number of ground wires (bundles): 2

| Conductor | Phase | X     | $Y_{\text{tower}}$ | $Y_{\text{min}}$ | Conductor |
|-----------|-------|-------|---------------------|-------------------|-----------|
| 1         | 1     | -42.000 | 68.000              | 68.000             | 1         |
| 2         | 2     | 0.000   | 68.000              | 68.000             | 1         |
| 3         | 3     | 42.000  | 68.000              | 68.000             | 1         |
| 4         | 0     | -29.500 | 108.000             | 108.000            | 2         |
| 5         | 0     | 29.500  | 108.000             | 108.000            | 2         |

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*Fig. 7 Graph 1*
R, L, AND C LINE PARAMETERS:

| Resistance matrix R_matrix(ohm/km) | Inductance matrix L_matrix (H/km) | Capacitance matrix C_matrix (F/km) |
|------------------------------------|----------------------------------|----------------------------------|
| 0.1071  0.0973  0.0950            | 0.0016  0.0008  0.0006            | 0.1166  -0.0213  -0.0058          |
| 0.0973  0.1105  0.0973            | 0.0008  0.0016  0.0008            | -0.0213  0.1212  -0.0213          |
| 0.0950  0.0973  0.1071            | 0.0006  0.0008  0.0016            | -0.0058  -0.0213  0.1166          |

Positive- & zero- sequence resistance [R1 Ro] (ohm/km): 0.0117 , 0.3013
Positive- & zero- sequence inductance [L1 Lo] (H/km): 8.6825e-04 , 2.9878e-03
Positive- & zero- sequence capacitance [C1 Co] (F/km): 1.3426e-08 , 8.5885e-09

Power Flow Control

To control power flow, it is desirable to be able to maintain or change quantities such as line impedances, bus voltage magnitudes, and phase angle differences. There are many power controller devices which affect some or all of these parameters. The well-studied FACTS devices are included in this power controller category.

- As shown in the model, when the switches of the LIM are operated, impedance of line L3 progressively increases up to the point where only one switch remains closed per switching module.
- With only one conductor in service per bundle power flows in line L2 and L3 are nearly equals even though L2 is 50% longer than L3. Power flows in line L1 becomes almost zero.
- This shows that LIMs have the capability of reducing power flows of overloaded transmission lines. The step changes beyond t=4 s shows that LIMs can also quickly vary the line impedance if required.
- Graph 2 shows the bus B2 sequence voltages and the sequence currents flowing out of B2 toward line L3. This is the line current of the back-to-back LIM.
- It can be seen that for all switch combinations used, the negative- and zero-sequence voltages and currents remain lower than the initial values obtained with all switches closed.
- Hence LIMs can be operated to produce power ramping or power step without increasing negative- and zero-sequence levels. Graph 3 shows that the voltages across the switches of the phase A switching module located on the bus B2 side.
- It can be seen that transient voltages remain within 35 kV which allows the use of medium voltage switching devices. The maximum rms voltage in steady-state, visible at t = 3.9s, is 13.4 kV.
With all switches closed, switch currents are initially 465 A rms.

With all but one switch opened at t=3.9 s, it can be seen that the switch current of subconductor 2 reaches 1533 A rms.

Hence, although the power flow in line L3 has been reduced by 17%, the subconductor current has increased by a 3.3 factor.

Such a current is large enough for simultaneously deicing by the Joule effect three subconductors (one per phase) in both 30-km BCL segments.

Once a first subconductor is de-iced in each bundle of both BCL segments, three other switch combinations can be used to completely de-ice the transmission line.

Note that the switch combination table provided in the example is appropriate for power flow control.

Other switch combination tables would be used to force specific subconductor de-icing sequence and avoid bundle rotation.

Note that if line currents had initially been too low for reaching a deicing level, it could have been possible to open the switches of one 30-km segment only.

The smaller impedance increase provided by one BCL segment would then lead to a higher current in the sub-conductors to de-ice.

Also, accordingly to the concept of the smart power grid where each line would be equipped with switching modules, impedance of line L2 could be increased to divert even more current into line L3.

**Fig.-8 Graph 2**

**Line De-icing**

- Graph 3 also shows the switch currents of the phase A switching module located on the bus B2 side.
- With all switches closed, switch currents are initially 465 A rms.
- With all but one switch opened at t=3.9 s, it can be seen that the switch current of subconductor 2 reaches 1533 A rms.
- Hence, although the power flow in line L3 has been reduced by 17%, the subconductor current has increased by a 3.3 factor.
- Such a current is large enough for simultaneously deicing by the Joule effect three subconductors (one per phase) in both 30-km BCL segments.
- Once a first subconductor is de-iced in each bundle of both BCL segments, three other switch combinations can be used to completely de-ice the transmission line.
- Note that the switch combination table provided in the example is appropriate for power flow control.
- Other switch combination tables would be used to force specific subconductor de-icing sequence and avoid bundle rotation.
- Note that if line currents had initially been too low for reaching a deicing level, it could have been possible to open the switches of one 30-km segment only.
- The smaller impedance increase provided by one BCL segment would then lead to a higher current in the sub-conductors to de-ice.
- Also, accordingly to the concept of the smart power grid where each line would be equipped with switching modules, impedance of line L2 could be increased to divert even more current into line L3.
The significance of intensive use of FACTS devices in the emerging electricity market environment demands more robust FACTS control methodologies. To control power flow, it is desirable to be able to maintain or change quantities such as line impedances, bus voltage magnitudes, and phase angle differences. There are many power controller devices which affect some or all of these parameters. Atmospheric icing may be problematic for many industries, including electric utilities. The combination of wind and ice could cause damages, sometimes leading to power outages. So, to improve power flow control and remove ice from transmission lines, a bundled control line impedance modulator is implemented here. It includes the concept of switching module and the result obtained when all switch are on and when one switch is open.
shows that the current increases to very high amount which in turn will melt the ice. The qualitative results presented in this study show that a LIM with snubbers presents better performance. Here we can see from results that how the value of current increased per conductor with the help of switching module and also the power flow is controlled by varying the impedance with the help of switching module.

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