POWER FLOW CONTROL IN A TRANSMISSION LINE USING D-FACTS DEVICES

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ABSTRACT

Flexible AC transmission systems (FACTS) devices can control power flow in the transmission system to voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. This variable reactance influences the electric power flow in the transmission line. This paper illustrates the flexibility of control that is achievable with D-FACTS devices. D-FACTS converters are single-phase and floating with respect to the ground, there is no high-voltage isolation required between the phases. The impact of installing D-FACTS devices is examined by studying the sensitivities of power system quantities such as voltage magnitude, voltage angle, bus power injections, line power flows, and real power losses with respect to line impedance. Sensitivities enable us to quantify the amount of control D-FACTS devices offer to the system. Independently controllable lines are selected for power flow control and appropriate locations to install D-FACTS devices for line flow control are determined. Then, D-FACTS device settings are selected to achieve desired line flow objectives.

Keywords - Power flow control, Distributed flexible AC transmission systems, TCSC

I. INTRODUCTION

A Flexible AC Transmission System incorporates power electronics and controllers to enhance controllability and increase transfer capability. This paper introduces the concept of a distributed static series compensator that uses multiple low-power single-phase inverters that attach to the transmission conductor and dynamically control the impedance of the transmission line, allowing control of active power flow on the line. The DSSC inverters are self-powered by induction from the line itself, float electrically on the transmission conductors, and are controlled using wireless or power line communication techniques. Implementation of system level control uses a large number of DSSC modules controlled as a group to realize active control of power flow. The DSSC can be used to either increase or decrease the effective line impedance, allowing current to be "pushed" away from or "pulled" into a transmission line. The DSSC concept overcomes some of the most serious limitations of FACTS devices, and points the way to a new approach for achieving power flow control–the use of Distributed FACTS or D-FACTS devices.

II. POWER FLOW CONTROL

FACTS devices are typically high-power high-voltage power converters, operating at 138–500 kV and 10–300 MVA, that are used to control power flow in the transmission and distribution network. For controlling power flow on transmission lines, the series elements clearly have the highest potential and impact. The real and reactive power flow, P and Q , along a transmission line connecting two voltage buses is governed by the two voltage magnitudes V_1 and V_2 and the voltage phase angle difference,

$$\delta = (\delta_1 - \delta_2)$$

as

$$P_{12} = \frac{V_1 V_2 \sin\delta}{X_L} \qquad (1)$$

and

$$Q_{12} = \frac{V_1^2 - V_1 V_2 \cos\delta}{X_L} \qquad (2)$$

where X_L is the impedance of the line, assumed to be purely inductive. A series compensator is typically used to increase or decrease the effective reactive impedance of the line, thus allowing control of real power flow between the two buses. D-FACTS devices can be made to communicate wirelessly by receiving commands for impedance injection changes.

The impedance change can be effected by series injection of a passive capacitive or inductive element in the line. Alternatively, a static inverter can be used to realize a controllable active loss-less element such as a negative or positive inductor or a synchronous fundamental voltage that is orthogonal to the line current [6,7]. In the latter case, the power flow depends on the injected quadrature voltage V_q as

$$P_{12} = \frac{V_1 V_2 \sin\delta}{X_L} - \frac{V_1 V_q \cos(\delta/2)}{X_L} \times \left[\frac{\sin(\delta/2)}{\sqrt{\left(\frac{v_1 + v_2}{2v_2}\right)^2 - \frac{v_1}{v_2}\cos^2(\delta/2)}} \right] \tag{3}$$

and the bracketed term is unity if $V_1=V_2=V$. Fig. 1 shows, for equal bus voltage magnitudes, the variation of power flow along a transmission line that can be achieved by injecting passive impedance or an active impedance [1].

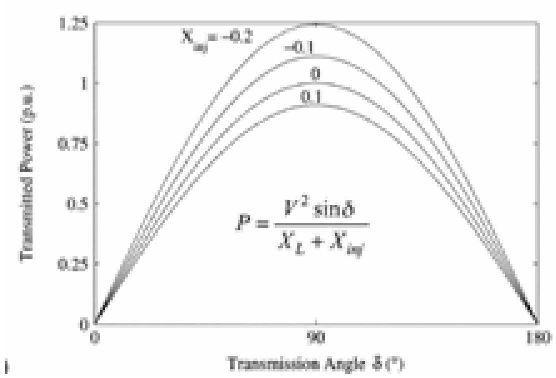

Fig.1. Passive impedance injection as p.u. of X_L (TCSC).

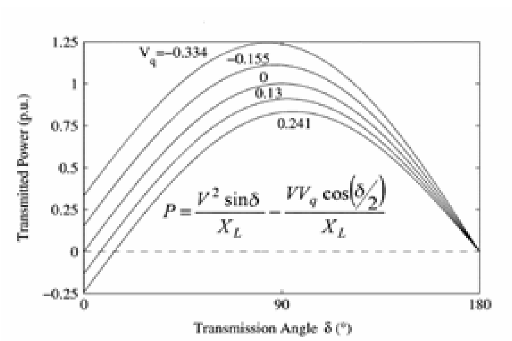

Fig.2. Quadrature voltage injection to achieve active impedance injection

III. CONTROL POTENTIAL OF D-FACTS DEVICES

D-FACTS devices control of one line affects the flows on all lines. The impact that the control of one line flow has on other line flows is specific to the system. If a system has only one loop, the flows are completely coupled and cannot be controlled independently. For any power system, it is useful to be able to determine the control potential available from D-FACTS devices. Analysis of the control of power systems with FACTS devices [12-14] has been examined, but primarily with respect to transient stability, where FACTS devices can be used for control of certain modes of the system. In this work, we are interested in the ability of D-FACTS devices to provide control over line flows throughout the system. When effective line impedances change, power flows redistribute in the system. Our perspective is to show through steady-state analysis the ability of D-FACTS devices to control the way power flows distribute throughout the system.

A. Identification of Independently Controllable Line Flows

In some scenarios, it may be clear, which lines need to be targeted for control. The need to operate the system securely is costly but crucial. D-FACTS devices can be used to relieve a known overloaded element such as a line or transformer. The ability to relieve an overloaded element through the use of D-FACTS control is by itself a strong advantage. Since an overloaded line or transformer can prevent many power transfers from being able to take place, reducing the flow through the overloaded element by even a few percent improves the operation of the power grid.

From a broader perspective, D-FACTS devices can be used throughout the system to provide the most comprehensive control. In order to provide the most complete and effective control for the entire system, it is necessary to identify how the control of line flows are related to each other. The coupling of the control of line flows is important to understand so that money and control effort are not wasted in attempts to independently control line flows which are highly coupled.

The following matrices show trivial cases where controls of line flows are completely decoupled (a) and decoupled (b):

a. $x_1 \quad x_2 \quad x_3$ b. $x_1 \quad x_2 \quad x_3$

$$\begin{matrix} p_{fl,1} \\ p_{fl,2} \\ p_{fl,3} \end{matrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \begin{matrix} p_{fl,1} \\ p_{fl,2} \\ p_{fl,3} \end{matrix} \begin{bmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{bmatrix}$$

In the completely decoupled case, the vectors are orthogonal and the angle between them is exactly 90 degrees. In the completely coupled case, the row vectors are perfectly aligned and the angle between them is exactly zero degrees. When the row vectors are perfectly aligned but point in opposite directions, the angle between them is 180 degrees, but they are still completely coupled. Thus, coupling can be determined by comparing the cosine of angles of vectors [15].

The cosine of the angle between two row vectors v1 and v2

$$\cos\theta_{v1v2} = \frac{v_1 . v_2}{\|v_1\|\|v_2\|} \tag{4}$$

of the total power flow to impedance sensitivity matrix □·□+□ will be called the coupling index. The coupling index has values between -1 and 1. When the coupling index has an absolute value of 1, there is complete correlation, either positive or negative, between the ways the two line flows respond to D-FACTS control. When the coupling index is zero, the line flows have the ability to be controlled independently.

B. Identification of Effective D FACTS Locations.

D-FACTS devices are unique because they are well-suited to be placed at multiple locations in the system where their use could be the most beneficial. Comparatively, if only one FACTS device is used, all support goes to the same place. However, reactive power support is most effective locally. Sensitivities can be used to identify lines with a high impact for particular applications. Lines with higher sensitivities are able to provide more control, whereas lines with sensitivities of zero have no impact. The locations for D-FACTS devices are found by determining the lines with the highest sensitivities for the objective. This approach to system implementation has resulted in large and complex converter installations and barriers that have, so far, limited the commercial success ofFACTS technology.

These include:

- High-cost resulting from device complexity and component requirements;
- Single point of failure can cause the entire system to shut down;
- Maintenance and on-site repair requirements for a complex
- Custom-engineered system adds significantly to system operating cost and increases mean time to repair (MTTR);
- Lumped nature of system and initial over-rating of devices to accommodate future growth provides poor return on investment (ROI);
- Custom engineered nature of system results in long design and build cycles, resulting in high system cost that will not easily scale down with volume. These limitations are overcome by our proposed D-FACTS system.

IV. TRANSMISSION LINE POWER FLOW CONTROL

Once appropriate lines are targeted for control and effective locations for D-FACTS devices are selected, the problem of power flow control needs to be solved. The goal of the problem can be stated as a desire to attain specified line flows on any number of independently controllable lines through the control of line impedance settings of D-FACTS devices on a specified number of lines.

It is not always possible to achieve a specified power flow on a line, so the line flow control equation,

$$\boldsymbol{P}_{\boldsymbol{flow},calc}(\boldsymbol{x}) = \boldsymbol{P}_{\boldsymbol{flow},spec}(\boldsymbol{x}) \tag{5}$$

does not always have a solution. This is acceptable because line flow control is merely an additional benefit. The level of importance of a solution of the power balance equations is much higher than the line flow control equations. For any power system application, the power balance equations $\boldsymbol{f}$ (p,q) must always be satisfied, but if some control over the power flow on a line can be achieved, that can be done as well.

Optimization methods are useful for problems that do not have a solution [16]. The line flow control problem can be examined in an optimization framework which reflects the intuition behind what is being accomplished with D-FACTS devices. The objective is to choose D-FACTS line impedance settings to minimize the differences between the actual power flows and the desired power flows. The objective function is f_0, where L is the number of line flows to be controlled:

$$f_o = \sum_{i=1} [p_{flow,calc}(x) - p_{flow,spec}(x)]_i^2 \tag{6}$$

The line flow control problem may be stated as follows:

The first constraint of (4) represents the AC power balance equations. The next two constraints are constraints on how much D-FACTS devices are able to change the line impedances. The gradient of *f0* is given by the following,

where the matrix ″ is formed from elements of the power flow to impedance total sensitivity matrix,. Thus, D-FACTS devices are able to control line flows on any lines with high enough sensitivities, not just their own line.

Important connections exist between sensitivities and optimization theory [17], [18]. The sensitivities which determine independently controllable line flows and effective D-FACTS locations also exactly provide the gradient needed to solve (15) using steepest descent. Steepest descent steps are given by the following, where α is a positive, scalar step size:

Knowledge of the total sensitivity of an equation to the control variables is enough to know how to minimize that function. Minimizing the objective function is equivalent to controlling real power line flows with D-FACTS devices.

V. D-FACTS CONTROL FOR A GENERAL PROBLEM

The same control approach is extended to other power system problems as follows

where f2 is the objective function for the problem of interest and D-FACTS devices are placed at locations in the system determined by the sensitivities of the objective function f2 to line impedance which are furthest from zero.

The direction of steepest descent is given by –f2, where f2 is the total derivative of the objective function with respect to x. Line impedance settings to minimize f2 are

where α is a positive, scalar step size. D-FACTS devices may then implement the final line impedance settings. This approach can be used to implement D-FACTS applications such as loss minimization and voltage control.

A. Loss Minimization and Voltage Control.

For loss minimization, if *f*2 is the losses, the total sensitivity to line impedances is given by *f*2 = K. For voltage control including both raising and lowering system voltages, *f*2 is the sum of the differences of the bus voltages from specified values. The gradient *f*2*,* is given by *f*2, = 2 () $_V$ where Φ_V, the sensitivities of voltages with respect to line impedance, are the lower section of the state to impedance sensitivity matrix, $\Phi = [_\theta, _V]^T$.

B. Comments on Other Solution Methods.

The steepest descent optimization approach is a logical choice because it requires only knowledge of the sensitivities and the ability to solve the power flow, and it guarantees movement toward the optimum. The ability to guarantee descent is important since the goal is to determine the extent of D-FACTS abilities.

One approach, often using Newton's method, treats the effective reactance of D-FACTS devices as state variables and solves the modified power flow equations for the line impedances in addition to the other state variables. Problems include that Newton's method does not guarantee descent, may not converge, and may not exhibit expected behavior if started far from the solution. If second order sensitivities can be calculated or approximated, the class of Newton-like methods [18] may be worthwhile to investigate. Newton-like methods also alleviate some of the problems with pure Newton's method.

VI. SCHEMATIC & SIMULATION DIAGRAM

A controlled transmission system can be made up of a large number, of DSSC modules, each module containing a small rated single phase inverter, a communications link and a single turn transformer (STT) that is mechanically clamped on to—and suspended from—the transmission line conductor.

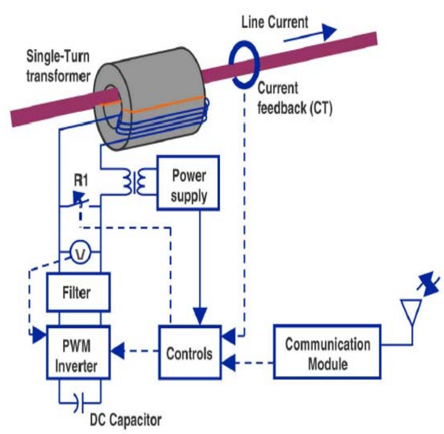

Fig..3. Schematic power circuit.

The STT (single turn transformer) uses the transmission conductor as a secondary winding, directly injecting the desired voltage into the cable itself. The inverter is self-powered by induction from the line, and can be controlled to inject a voltage that is orthogonal to the line current directly into the conductor. The module can either be suspended from the conductor or configured as a replacement for the conductor support clamp on an insulator. Further, since it does not require supporting phase-ground insulation, the module can easily be applied at any transmission voltage level.

When the transmission line is not powered up, the STT is bypassed by a normally closed relay contact

(R1) that opens once control power is available. A current transformer is used to generate control power, allowing the DSSC module to operates as long as the line current is greater than a minimum level. The line appears to the inverter as an inductive current source. The single phase inverter uses four IGBT devices along with an output LC filter and a dc bus capacitance. The inverter output voltage is controlled using pulse width modulation techniques, and has two components. The first is in quadrature with the line current, and represents the desired impedance to be injected. The second is in phase with the line current, and allows compensation of power losses in the inverter, and regulation of the dc bus of the inverter. System commands for gradual changes are received from a central control center using a wireless or power line communication (PLC) technique.

The STT is a key component of the DSSC module. It is designed such that the module can be clamped onto an existing transmission line. The inverters present clearly demonstrate that the semiconductors and components used are commercially available in very high volumes for the motor drives, UPS, and automotive industries, thus validating the potential for realizing low cost.

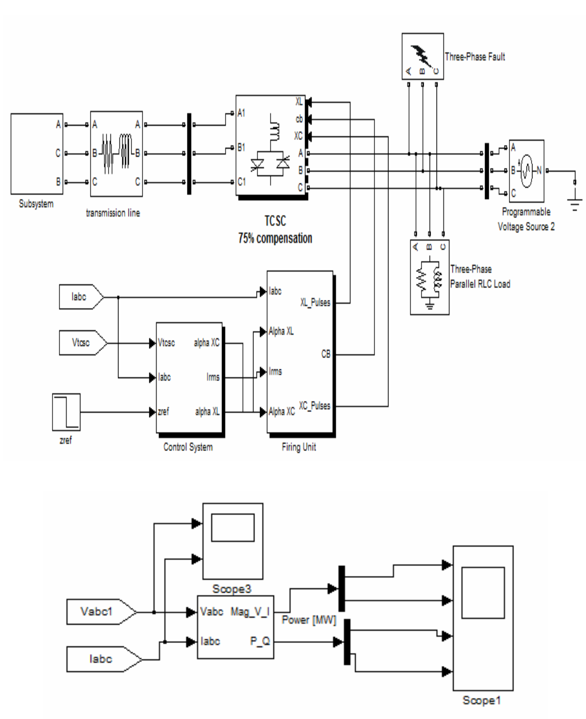

Fig.4. Simulation diagram

The above figure shows the simulation diagram for three phase system in a transmission line which is given to the TCSC which gives 75% compensation .Now the TCSC is analyzed with any type of fault such as Line to phase or phase to line or phase to phase etc…

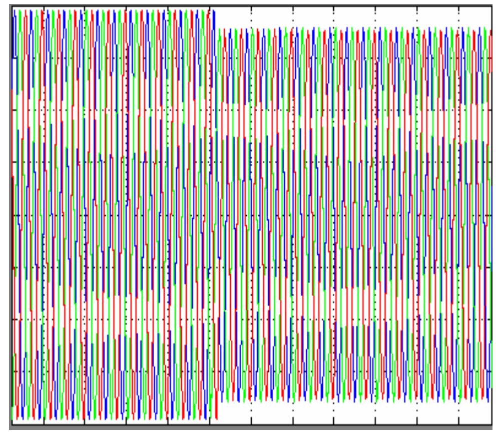

Fig.5. Voltage sag due to fault

The above figure shows the voltage output and the sag present in the output and this can be compensated using TCSC in our circuit. In the same manner the other types of faults can also be analyzed and the output can be obtained by reducing faults of any type.

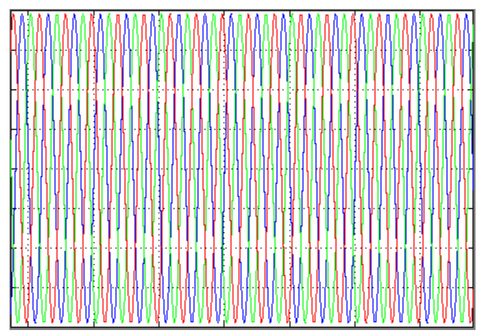

Fig.6. Voltage after compensation

The above figure shows the voltage output by using TCSC in which the voltage is compensated by 75% and the sag is removed thereby the performance of the system is improved.

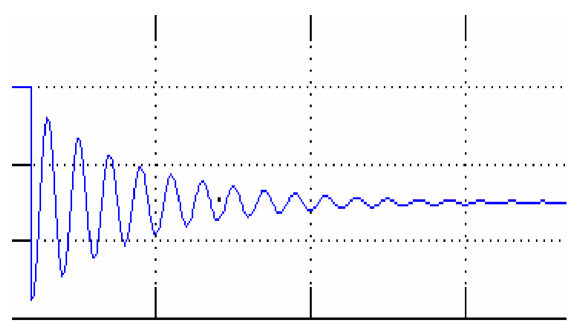

Fig.7. Active Power

The Active power output for the proposed system is given in the above figure.

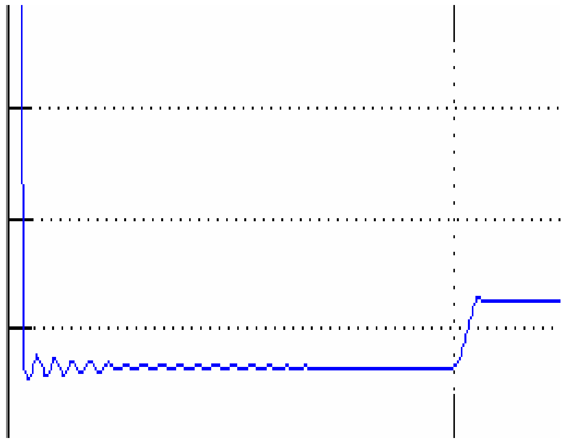

Fig.8. Reactive Power

The reactive power output is given for the proposed system is given in the above figure. This can also be further reduced in future.

VII. CONCLUSION

D-FACTS devices have the unique ability to be incrementally installed on multiple lines throughout a system to provide power flow control wherever needed. Effective D-FACTS device locations and independently controllable flows can be identified from sensitivities. After D-FACTS devices are installed in certain fixed locations, their control objective can easily be changed to target other lines flows.

Thus, D-FACTS devices can provide widespread, versatile control for power systems. In this paper, the successful control of line flows with D-FACTS devices is presented for two test systems. A general approach for line flow control with D-FACTS devices is developed. The use of sensitivities in solving nonlinear problems can be extrapolated to any application of interest and for any system given.

A controlled transmission line implemented with multiple DSSC modules can realize significant benefits at a system level. At the highest level, it can:

- enhance asset utilization;
- reduce system congestion;
- increase available transfer capacity (ATC) of the system; Thus by using this system the faults present can be minimized as well as compensated.

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