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A New Control Strategy For Distributed Static Compensators Considering Transmission Reactive Flow Constraints

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ABSTRACT

A static synchronous compensator (STATCOM) is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power.

This paper presents a new control strategy for a distributed static compensator (also known as distributed STATCOM or DSTATCOM), configured to regulate the reactive (VAr) flow at a point in a transmission system. This new control strategy takes into account the operating VAr limits of that reactive flow in determining the steady-state output of the DSTATCOM. The new control strategy applies a slow reset regulator (SRR) to slowly bias the VAr set point of the DSTATCOM master controller to maintain its steady-state output within a target bandwidth.

The operating result maintains an appropriate VAr reserve level from the DSTATCOM for dynamic events in the system. This paper also presents a new algorithm to calculate the operating constraints of the SRR that reflect the VAr flow at the local or remote point in the transmission system and the allowable VAr thresholds for that flow.

These allowable thresholds can be utilized to the full extent to lower the steady-state output of the DSTATCOM, maximize its VAr reserve for dynamic events and reduce equipment and associated system operating losses. Modeling, implementation, and

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simulation of an engineering project show that the new control strategy and algorithm are functioning properly as expected.

INTRODUCTION:

Many SVC or STATCOM applications require an appropriate reactive power (VAr) reserve capacity to handle dynamic events to improve system voltage stability.

The SRR in the SVC or STATCOM control system is used to slowly return the SVC or STATCOM to a predefined value (which is usually a low output level relative to the rating) of reactive power output following a contingency, so that it has maximum reactive reserve for dynamic events.

These applications are based on a voltage regulation (Vcontrol) technique, that is, the voltage reference set point of the SVC or STATCOM is slowly being adjusted by the SRR as necessary.

Designs and development of various STATCOM controls and applications. The authors of this paper are not aware of the SRR concept used in the reactive () control mode for either the SVC or STATCOM system either in the published literature or real transmission system applications.

This resulted in an engineering development project to examine the SRR strategy with the -control system indicate the breadth of research, designs, and development of various STATCOM controls and applications.



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For some transmission applications or renewable energy integrations where the -control mode is executed to control the VAr flow at a local or remote point in the transmission system, a distributed approach to reactive power control and voltage support applies STATCOM systems in multiple locations where voltage issues and reactive power shortage exist.

This type of STATCOM system design is referred to as the distributed STATCOM system or the DSTATCOM system in this paper.

This distributed approach achieves redundancy which eliminates the total loss of reactive power support in the area in the event of a single unit being taken out of service. In these applications, multiple devices in one DSTATCOM system or multiple DSTATCOM systems in one area are usually coordinated to share the required compensation level through droop controls.

EXISTING SYSTEM:

Te concept of the slow reset regulator (SRR) has been proposed or used for some FACTS device such as static VA compensators (SVC) or static compensator (STATCOM) for system voltage control applications. The new control strategy applies a slow reset regulator (SRR) to slowly bias the VAr set point of the DSTATCOM master controller to maintain its steady state output within a target bandwidth.

The operating result maintains an appropriate VAr reserve level from the DSTATCOM for dynamic events in the system. This paper also presents a new algorithm to calculate the operating constraints of the SRR that reflect the VAr flow at the local or remote point in the

transmission system and the allowable VAr thresholds for that flow.

PROPOSED SYSTEM:

A modeling block diagram of the DSTATCOM master controller in the Q-control mode with the SRR (red lines) and interface to a transmission system where multiple renewable power plants are also connected. This figure represents an engineering application at a wind generation hub where the transmission operator usually requires a minimum impact on voltage and VAr flow caused by the variable wind generation.

In the diagram, the DSTATCOM is configured to control the VAr flow at the point of interconnection (POI) of the renewable plants, which is a 230 kV bus in the transmission system miles away from the plant location. This control configuration can also be used for any other transmission applications where the VAr flow at a local or remote point in the system needs to be regulated.

For example, the change in power transfer (import or export) between two areas may cause VAr flow swings and hence large reactive losses in the transmission system. In this case, the VAr flows on the transfer paths of the transmission system may be controlled by substation-based DSTATCOM systems with similar control configurations.



Fig. 1. Schematic diagram of one device in a DSTATCOM system.



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ADVANTAGES:

- Maintain its steady state output within a target bandwidth.
- Maximize its VAr reserve for dynamic events and reduce equipment and associated system operating losses.

BLOCK DIAGRAM:



MODELING OF NEW CONTROL STRATEGY AND ALGORITHM FOR THE CALCULATION OF OPERATION CONSTRAINTS

Brief Description of the DSTATCOM

Fig. 1 shows a schematic diagram of one device in a DSTATCOM system which uses IGBT2-based dc-to-ac inverters. The inverter creates an output ac voltage that is controlled using pulse width modulation technologies to produce either leading (capacitive) or lagging (inductive) variable reactive current (or) into the utility system. The inverter-based DSTATCOM can maintain a constant current in or out of the system during low or high voltages and, thus, its reactive power is directly proportional to the system voltage. In addition, the

DSTATCOM has a unique short-time rating of more than 260% for up to 3 s. This short-time capacitive or inductive rating provides significant dynamic reactive compensation to maintain system voltage stability during dynamic events [28].

The DSTATCOM can be configured to control and coordinate its output with slower reactive support elements, such as switchable capacitors or reactors for system voltage support. Such control and coordination for an engineering project have been discussed in [29]. For illustrative purposes, a sample simulation is plotted in Fig. 2 to show the DSTATCOM reactive output (red line) versus time that starts with a small value and then increases very fast following a contingency event at 1 s, then decreases to a new lower setpoint when three capacitor banks (green line) are switched in with a delay time of 10 s.

DSTATCOM Master Controller With the -Control Mode Fig. 3 shows a modeling block diagram of the DSTATCOM master controller in the -control mode with the SRR (red lines) and interface to a transmission system where multiple renew- able power plants are also connected. This figure represents an engineering application at a wind generation hub where the transmission operator usually requires a minimum impact on voltage and VAr flow caused by the variable wind generation. In the diagram, the DSTATCOM is configured to control the VAr flow at the point of interconnection (POI) of the renewable plants, which is a 230-kV bus in the transmission system miles away from the plant location. This control configuration can also be used for any other transmission applications where the VAr flow at a local or remote point in the system needs to be regulated. For example, the change in power transfer (import or ex- port) between two areas may cause VAr flow swings and, hence, large reactive losses in the transmission system. In this case, the VAr flows on the transfer paths of the transmission system may be controlled by substation-based DSTATCOM systems with similar control configurations.



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In the control configuration under study, the VAr setpoint in the -control mode is settable and adjustable through the supervisory control and data acquistion (SCADA) system by the system operator to match the VAr flow target at the POI. For example, some utilities require this target to be a very small value, that is, the VAr flow interchange with the system at the POI is controlled to be close to zero. Other utilities allow this target to be controlled within the VAr flow thresholds which are also settable and adjustable via SCADA by the system operator. In the implementation of this type of control configuration, the DSTATCOM master control system requires as input:

1) local measurements such as P, Q, V, and I, etc.;

2) remote measurements of P, Q, V, and I through communi- cation systems;





3) The calculation of remote parameters using local measurements in a technique that is called line drop compensation (LDC), when the remote measurements are unavailable.

The DSTATCOM master controller is based on a propor- tional-plus-integral (PI) controller with the operating limits (and in Fig. 3) calculated based on the operating point and short-time rating of the DSTATCOM. This DSTATCOM master controller is

also configured to con- trol and coordinate the inverter output with switched shunt de- vices (SSDs). These devices include mechanically switched re- actors (MSRs) located in the same plant location or mechanically controlled capacitors in a remote location (e.g., 230-kV MSC in Fig. 3) for system reactive power and voltage support.

New Control Strategy and Modeling

The new control strategy applies the SRR to slowly bias the VAr setpoint of the DSTATCOM operating in the -control mode to maintain the steady-state output of the DSTATCOM within a predefined target bandwidth (i.e., in Fig. 3). This new feature is different when compared to standard V-con- trol-based SRR [1]-[3] that forces the output to zero indepen- dent of other observations. This new control strategy only al- lows the output to move toward zero within the operating range of the VAr flow target level at the local or remote point. Other transmission system constraints or generation sources may also require the limitation of that VAr flow. The SRR addition allows the DSTATCOM to work within the allowable range by moving the operating output point toward a low target value. This can minimize the steady-state output of the equipment and associ- ated operating losses and maximize the VAr reserve for dynamic events in the transmission system.

The -control-based SRR, as used in the new control strategy, is essentially a proportional-integral (PI) controller with varying control or operation constraints, in Fig. 3) as determined or calculated by the allowable VAr flow thresholds and the actual VAr flow at the remote point in the transmission system (e.g., the POI for a renewable resource hub). The output of this PI controller is added to the VAr setpoint of the DSTATCOM. From Fig. 3, the input to the DSTATCOM master controller is

 $DST_{\text{INPUT}} = VAr_{\text{SETPOINT}} - Q_{\text{REMOTE}}$

 $-SRR_{OUTPUT}$ + Other Signals (1)

where is the input to the DSTATCOM master controller, is the VAr setpoint for the DSTATCOM, is the actual VAr flow at the remote



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point in the trans- mission system (e.g., at the POI), is the output of the SRR for biasing the VAr setpoint of the DSTATCOM, and other signals (which may include the system voltage and real power at the local or remote point or the status of the remote 230-kV MSC, etc.).

The tuning of this PI controller and calculation of its opera- tion constraints are important for SRR operation. In general, the PI controller parameters are tuned such that the SRR begins to regulate over a relatively long period of time after system dynamics (caused by faults, line trips, loss of renewable or conventional generation, etc.) have passed and the system has almost settled down to a new operating point. The operating constraints are determined and calculated based on the allowable VAr flow thresholds and the actual VAr flow at the remote point in the system, which is described in the next subsection.

New Algorithm for the Calculation of SRR Operation Constraints

The control-based SRR operating constraints and in Fig. 3 are varying with, and calculated based on the measurement of the actual VAr flow and the allowable VAr flow range at the selected target system location. It can also be calculated by using an LDC algorithm and local measurements of voltage, real power, and reactive power at the local plant location. In Fig. 3, the selected target system location is assumed to be the POI for the renewable power plants, which is a 230-kV bus in the transmission system miles away from the plant location. The calculation of the SRR operation constraints is as follows:

$$Q_{\text{UPPER, ERROR}} = Q_{\text{UPPERTOL}} - Q_{\text{FLOW}}$$
(2)

$$Q_{\text{LOWER, ERROR}} = Q_{\text{LOWERTOL}} + Q_{\text{FLOW}}$$
(3)

$$Q_{\text{RMAX}} = MAX[0, Q_{\text{UPPER, ERROR}}]$$
(4)

$$Q_{\text{RMIN}} = MIN[0, Q_{\text{LOWER, ERROR}}]$$
(5)
IF $Q_{\text{RMAX}} > Q_{\text{UPPERTOL}},$ (6)

$$IF Q_{\text{RMIN}} < Q_{\text{UPPERTOL}},$$
(6)

$$SET Q_{\rm RMIN} = Q_{\rm LOWERTOL} \tag{7}$$

where

- Q_{UPPERTOL} and Q_{LOWERTOL} are upper and lower VAr flow limiting values at the POI;
- 2) Q_{FLOW} is the actual VAr flow at the POI;



Fig. 4. Simulation system with the DSTATCOM-based RCS on the -control with SRR and renewable power plants. (The numbers in the figure represent bus voltages in per unit and kilovolts and branch power flows in megawatts and megavolt-amperes.)

- Q_{UPPER,ERROR} and Q_{LOWER,ERROR} are the differences between the upper or lower VAr flow tolerance and the actual VAr flow at the POI;
- Q_{RMAX} and Q_{RMIN} are the upper and lower SRR operation constraints.

IMPLEMENTATION, SIMULATIONS, AND CASE STUDIES

Description of the Simulation System

The new control strategy with the -control-based SRR and the new algorithm for calculating the SRR operation constraints described in the previous section were implemented in a dy- namic simulation model of the S&C PureWave DSTATCOM master control system in a widely used power system simu- lator, that is, PSS/E [30]. Dynamic simulations were performed to verify the proper operation of the implemented new control strategy and algorithm in the model.

Fig. 4 is a one-line diagram from the aforementioned simu- lator to show part of a real transmission system where an en- gineering project was installed including a DSTATCOM-based reactive compensation system (RCS) with SRR and two renew- able power plants



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which have a total capacity of approximately 550 MW. The RCS consists of the following major equipment:

- one 15-MVAr DSTATCOM;
- four 34.5-kV, 11-MVAr mechanically switched reactors [MSRs, collectively referred to as switched shunt devices (SSDs)];
- two 230-kV, 60-MVAr mechanically switched capacitors (MSC).

The RCS is required to control the VAr flow at the POI (230-kV bus in the transmission system miles away from the plant location) within the thresholds set by the system operator via SCADA with varying output of renewable energy production or other changing system conditions. At the same time, the DSTATCOM operates at a low output (as possible in the steady-state condition) to maximize the VAr reserve for contingency events and to reduce equipment and associated operating losses. The SSD is controlled and switched by the DSTATCOM master controller as part of steady-state and dynamic voltage and reactive support. The 230-kV MSC may be controlled by the DSTATCOM master control system or with an independent controller. The renewable powerplants operate on an approximate unity power factor.



Fig. 5. DSTATCOM output response without with the slow reset regulator after a step change (Increase) in the setpoint (red without the SRR; green with the SRR).

Response to a Step Change in VAr Set Point

In this simulation, a step change (increase or decrease) was applied in the setpoint of the DSTATCOM master controller, and the output of the DSTATCOM following the disturbance was monitored. The predisturbance

condition of the system is shown in Fig. 4 where the VAr flow at the POI is about 2.5 MVAr, and the DSTATCOM has a zero output.

Figs. 5 and 6 show the simulation plots following the set- point step change. It is shown from the figures that the SRR is controlling the DSTATCOM output (green lines) to be within the target bandwidth 0.5 p.u. (specified in this simulation) after the disturbance. This indicates that the SRR is functioning and slowly biasing the setpoint to meet the target bandwidth. Without the SRR, the DSTATCOM output (red lines) settles at approximately 0.9 p.u. after the step change as expected. The change in the DSTATCOM output following the disturbance is being offset or balanced by other system VAr sources, since the SSD and the 230-kV MSC do not switch in this simulation. This simulation shows that the -control-based SRR is responding properly as expected.

Case Studies

In these studies, the allowable VAr flow thresholds at the POI were set to different values and the target bandwidth (i.e., in Fig. 3) of the DSTATCOM was set to a small value so that the steady-state output of the DSTATCOM is controlled by the SRR to be close to the target value within the VAr flow thresholds and to maximize the dynamic VAr reserve for contingency events. The following cases, parameters, and disturbances were simulated:

target bandwidth $\pm I_{DBD} = \pm 0.05$ p.u.



Fig. 6. DSTATCOM output response without with the slow reset regulator after a step change (Decrease) in the setpoint (red without the SRR; green with the SRR)



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TABLE ISUMMARY OF SIMULATION RESULTS

| Case No. | SRR | Allowable VAr Flow at POI (MVAr)* | DSTATCOM Output (MVAr)* | Actual VAr Flow at POI (MVAr)** |
|-------------|-----|---|-------------------------------|---------------------------------------|
| 1 | No | ±25 | -5.8 | -0.4 |
| 2 | Yes | ±25 | -0.4 | -15.5 |
| 3 | Yes | ±10 | -2.5 | -9.9 |
| 4 | Yes | ±5 | -4.2 | -5.1 |

Positive is capacitive; negative is inductive.

** Positive is into the system; negative is from the system



Fig. 7. DSTATCOM output responses without the SRR (red Case 1) and with the SRR (green Case 2; blue Case 3; black Case 4).

- · allowable VAr flow thresholds at the POI:
 - Case1 = ± 25 MVAr (without the SRR);
 - Case2 = ± 25 MVAr (with the SRR);
 - Case3 = ± 10 MVAr (with the SRR);
 - Case4 = ± 5 MVAr (with the SRR).
- contingency: Loss of the Renewable Power Plant I and one 230-kV capacitor bank to simulate variable renewable generation production.
- SRR operation constraints (Q_{RMAX} and Q_{RMIN} in Fig. 3) are calculated according to (2)–(7) in Section II-D.

In all of these cases, the SSD was set to operate as necessary during dynamics following the contingency. The remaining 230-kV capacitor bank does not switch following the contingency.

Table I summarizes the results of the case studies. The higher the allowable VAr flow thresholds at the POI, the lower the

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Fig. 8. VAr flow responses at the POI without the SRR (red Case 1) and with the SRR (green Case 2; blue Case 3; black Case 4).











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DSTATCOM output is adjusted by the SRR, which is functioning as expected. The details of post contingency power flows are shown in Figs. 7–12 and will be discussed.



Fig. 11. Postcontingency power flow with the slow reset regulator (Case 3, allowable VAr flow thresholds at the POI 10 MVAr).



Fig. 12. Postcontingency power flow with the slow reset regulator (Case 4, allowable VAr flow thresholds at the 5 MVAr).

Fig. 7 shows the DSTATCOM outputs without the SRR (red Case 1) and with the SRR (green Case 2); (blue Case 3); (black Case 4). Fig. 8 shows the VAr flow

responses at the POI without the SRR (red Case 1) and with the SRR (green Case 2); (blue Case 3); (black Case 4), which are following the changes in the DSTATCOM output in each case while honoring the VAr flow thresholds at the POI

Without the SRR, the DSTATCOM output settles at approx- imately 0.77 p.u. (Fig. 7) or absorbs 5.8 MVAr and the VAr flow at the POI settles at 0.4 MVAr (Fig. 9).

With the SRR in operation, the DSTATCOM output is brought within a 0.05-p.u. bandwidth or 0.4 MVAr (Fig. 10) when the actual VAr flow at the POI is within the VAr flow thresholds. This is shown in Case 2 where the VAr flow thresh- olds are set to 25 MVAr and the actual VAr flow at the POI is 15.5 MVAr (Fig. 10). Thus, the benefit of using the allowable VAr flow thresholds is that the steady-state output of the DSTATCOM and its associated operating losses can be minimized, and the VAr reserve from the equipment can be maximized for dynamic events in the system.

When the actual VAr flow is at the threshold, the operation constraints of the SRR would be zero according to (2)-(7) in Section II-D. Thus, there is no regulation room for the SRR and it stops regulation, and the DSTATCOM output settles at the value corresponding to the VAr flow threshold at the POI. This is shown in Cases 3 and 4 where the DSTATCOM at 2.5 MVAr and 4.2 MVAr, respectively, and settles the VAr flow at the POI is 9.9 MVAr and 5.1 MVAr, respectively (Figs. 11 and 12). As long as the VAR flow thresholds are nonzero, the benefit of the SRR regulation can be seen because the DSTATCOM does not need to operate at the full capacitive or inductive output, a condition with little dynamic VAr reserve that usually causes the highest operating losses.

These case studies further show that the -controlbased SRR is functioning properly as expected under either the nonlimiting or limiting VAr flow condition at the POI.



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CONCLUSION

This paper presented a new control strategy that a slow reset regulator (SRR) in the applies DSTATCOM master control system operating with the control mode and a new algorithm for calculating the SRR operation constraints that reflect the actual VAr flow at a local or remote point in a transmission system and the thresholds for that flow. The new control and calculation algorithm have strategy been implemented in a dynamic simulation model of the DSTATCOM operating in the -control mode in a widely used power system simulator. The implemented control strategy and calculation algorithm were simulated and applied in a real transmission system representing an engineering project which includes a DSTATCOM-based reactive compensation system and multiple renewable powerplants where the -control mode was used to regulate the transmission VAr flow at a remote point in the transmission system. The model testing and case studies showed that the new control strategy and algorithm are functioning properly as expected.

slowly The SRR drives the output of the DSTATCOM with the -control mode toward a low target value within several minutes after a system change that results in high VAr output of the equipment, while still observing operating parameters, thus maintaining a high level of dynamic VAr reserve for trans- mission voltage stability support under dynamic events. The DSTATCOM has been applied to several engineering projects that required 90% to 100% of the equipment MVAr rating for such dynamic VAr reserve.

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