The Use of Static Synchronous Series Compensator for Improving Power System Stability in Response to Selective-Pole Switching

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Abstract—This paper presents an adaptive short-time compensation scheme for improving power system stability. The proposed compensation is based on the use of Static Synchronous Series Compensator (SSSC), which provides the needed phase-wise compensation resulting from selective-pole switching of parallel transmission lines. The transmission system is balanced during the dead-time; time lapsed from fault clearing to high-speed reclosing (HSR). The validity and effectiveness of the proposed compensation scheme in enhancing power system stability are demonstrated through time-domain simulation studies on a multi-machine power system using the EMTP-RV program.

Index Terms—FACTS Controllers, power system stability, static synchronous series compensator, selective-pole switching.

I. INTRODUCTION

Selective-pole switching of a transmission line is the tripping and high-speed reclosing of only the circuit-breaker poles of the faulted phases [1]. With such a switching process, one pole would be tripped and reclosed for a single line-to-ground fault (single-pole reclosing), two poles for a line-to-line or a double line-to-ground fault, and all the three poles for a three-phase fault.

Although selective-pole switching of parallel transmission lines would improve significantly the system stability, it has been seldom, if ever used, for clearing line-to-line and double line-to-ground faults [2], [3]. The reason is the concern for the generator rotor excessive heating due to the negative-sequence currents flowing in the generator as the result of the unbalanced operation during the dead-time between fault clearing and line reclosing. Moreover, the negative-sequence current produces a double frequency (120 Hz) electromagnetic torque component which could excite one of the torsional frequencies of the turbine-blades [4].

In the studies presented in this paper, it is proposed to clear unsymmetrical faults, namely line-to-line, single and double line-to-ground faults on parallel transmission lines using selective-pole switching. The transmission system is then balanced (adaptive short-time compensation) during the dead-time between fault clearing and high-speed reclosing (HSR) using an existing Static Synchronous Series Compensator (SSSC) [5], [6]. The main advantages of such a scheme are as follows [7]:

1. The pre-fault transmission system capacity is restored immediately after fault clearing not after reclosing. This will greatly enhance the system stability.
2. Since the system balance is restored, the adverse effects of the negative sequence currents are eliminated.

The validity and effectiveness of the proposed scheme are demonstrated through time-domain simulation studies on a test benchmark system using the EMTP-RV program.

II. TEST BENCHMARK

The test Benchmark used for the study is shown in Fig. 1. This Benchmark system was proposed and described in details in [8]. It was developed and recommended to be used for testing FACTS models. The Benchmark consists of twelve busses, six 230 kV transmission lines and one 345-kV link (between busses 7 and 8). Power flow studies have revealed that in the event of a loss of generation from G3, or a loss of the transmission line between busses 4 and 5, line 1–6 is overloaded while the transmission capacity of the parallel path through the 345 kV double-circuit transmission lines 7–8 is underutilized. Moreover, small signal stability studies have shown that the system has poorly damped inter-area oscillation modes. One option for relieving this congestion and damping the inter-area oscillations is to install an SSSC on line 7–8 as shown in Fig. 1.

![Fig.1. Test benchmark.](image-url)
For the time-domain simulation studies, the synchronous generators are represented in the $d-q-o$ reference frame. The transmission lines are modeled as a transposed lumped parameters using series impedance representation. The infinite bus is represented as a bus having constant amplitude sinusoidal voltage at the synchronous frequency. Circuit-breakers are represented as ideal switches which can open at current zero crossing. Dynamics of the turbine-generator excitation and governor systems are included in the simulation model. The EMTP-RV is the used simulation study tool.

III. PRINCIPLE OF THE ADAPTIVE SHORT TIME COMPENSATION SCHEME

The basic intent of the adaptive short-time compensation scheme is to balance the transmission system during the period between clearing and reclosing unsymmetrical faults using selective-pole switching. The short-time compensation is performed using the existing SSSC shown in Fig. 1. Fig. 2 illustrates the process of the short-term compensation, which is described in the following:

1. Detection of the fault, type and faulted phase(s) is carried out by the protection system.
2. Two signals are provided by the relaying and control system, one for tripping the faulted circuits (a1, b1, Fig. 2(a)), and the other for operating the SSSC in a phase imbalanced mode. The latter action will balance the transmission system if the SSSC is injecting equal capacitive voltages in phases a and b such that this voltage is compensating one half of the inductive reactance of one circuit of the transmission line as shown in Fig. 2(b).

![Diagram](image)

**Fig. 2.** Adaptive short-time compensation of a double line-to-ground fault: (a) basic scheme, (b) equivalent circuit of the transmission system.

3. HSR is performed and the SSSC imbalance mode of operation is disabled.

IV. IMPLEMENTATION OF SSSC IN THE UNBALANCED OPERATION MODES

This section describes the implementation and control of the adapted SSSC. The developed SSSC model provides the implementation options of being three phase SSSC, two phase SSSC and/or single phase SSSC configuration. The unbalanced operation of the SSSC is achieved by controlling the injected voltage of each phase to the desired value. Fig. 3 shows the block-diagram of SSSC controller.

The difference between the injected voltage ($v_{inj} = v - v_l$ in p.u.) and the voltage reference value is processed in a PI controller. The output of the PI controller acts as a modulation index for the PWM converter. Positive value of $v_{ref}$ is taken for capacitive compensation while negative value is taken for inductive compensation. Only the capacitive operation of SSSC is considered in this paper.

![Diagram](image)

**Fig. 3.** Block diagram of an SSSC controller.

The DC voltage is controlled at a reference value by implementing a separate PI controller. The difference between the actual DC voltage and the reference DC voltage is processed in this controller to generate a small angle $\Delta \theta_{dc}$ for charging/discharging the DC capacitor. The angle $\Delta \theta_{dc}$ is added to the PLL (Phase Locked Loop) output angle. The value $\pm \pi/2$ is added to the angle $\theta$ so that the injected voltage is in quadrature with the transmission phase current, quadrature leading for inductive compensation and quadrature lagging for capacitive compensation respectively. The cosine reference wave and a triangular wave are compared according to gate signal generation logic and gate signal generation logic.

Each single-phase SSSC is modeled using a three-level IGBT based PWM (Pulse Width Modulation) converter. The schematic diagram of the SSSC connected to the transmission system is shown in Fig. 4. The line voltage and current as well as other controllable variables are measured and passed to a controller. A series transformer is used to inject the respective voltage into the transmission line. An LC filter is used to filter out the high-frequency switching noises. The DC capacitor size is selected such that the DC transient voltage overshoot is limited to 20%. Technical detail of the single-phase SSSC implementation is given in the Appendix. The controller parameters were adjusted through repeated time domain simulations for different operating conditions. The controller...
The paper presented the potential use of an existing SSSC in improving system stability during selective-pole switching of parallel transmission lines. The effectiveness of the proposed adaptive short time compensation scheme is demonstrated through detailed digital computer simulations on a benchmark test system. The results of the investigations have shown that adaptive short-time compensation of unsymmetrical faults tripped with selective-pole switching enhances significantly the system stability. Furthermore, since the pre-fault transmission system capacity is restored immediately after fault clearing, reclosing of the tripped conductors can be delayed (the dead-time can be increased) to ensure a complete extinction of the secondary arc. This will increase the potential of a successful reclosure and, therefore, further improvement of the system stability.
Fig. 7. Generator load angle responses during successful reclosing of a 3-30 cycles line-to-line fault on line 7-8.

Fig. 8. Generator load angle responses during successful reclosing of a 3-30 cycles single line-to-ground fault on line 7-8.

Fig. 9. Generator 3 field current response during successful reclosing of a 3-30 cycles single line-to-ground fault on line 7-8: (a) single-pole switching and reclosing, (b) single-pole switching and adaptive short-time compensation.

APPENDIX I

TABLE I

| Controller gains | $K_p = 2.5$, $K_i = 100$ | $K_{DC} = 0.5$, $K_{DC} = 50$ |

TABLE II

SSSC PARAMETERS

<table>
<thead>
<tr>
<th>Coupling transformers</th>
<th>3 x 42 MVA, 42 kV/6.6 kV (converter side)</th>
<th>$s_v = 0.1$ p.u.</th>
<th>$s_i = 0.002$ p.u.</th>
<th>Three-level PWM</th>
<th>$L = 0.09$ mH</th>
<th>$C = 0.09$ mF</th>
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<tr>
<td>LC Filter</td>
<td>0.8 mF</td>
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<td>DC side base voltage</td>
<td>$f_c = 1980$ Hz</td>
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<tr>
<td>DC capacitor</td>
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<tr>
<td>Carrier signal frequency</td>
<td>$f_c = 1980$ Hz</td>
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APPENDIX II

IMPROVEMENT OF POWER SYSTEM STABILITY USING SINGLE-POLE SWITCHING OF LINE-TO-LINE FAULTS ON SINGLE-CIRCUITS TRANSMISSION LINES

This section demonstrates the improvement of power system stability by using single-pole switching and reclosing of line-to-line faults on single-circuit transmission lines. In this context, the test benchmark is modified by assuming that line 7-8 is a single-circuit transmission line as shown in Fig. 10.

Fig. 11 illustrates the load angle responses of generators $G_2$, $G_3$, and $G_4$ during successful reclosing of a 3-30 cycles line-to-line fault (phases a1&b1) on line 7-8 for the cases of triple-pole switching (TPS) and single-pole switching (SPS). Fig. 12 illustrates generator $G_3$ electrical power response during the same fault of Fig. 11. As it can be seen from Fig. 11, the maximum generator swing angles in the case of the single-pole switching are much smaller than those corresponding to triple-pole switching. Moreover, Fig. 12 shows that the low-frequency oscillations in the electrical power of generator 3 are more damped in the case of single-pole switching than in the case of triple-pole switching. This is a clear evidence of the advantage of single-pole switching of line-to-line faults.

Fig. 10. Modified test benchmark with L7-8 is a single-circuit transmission line.

REFERENCES


Fig. 11. Generator load angle responses during successful reclosing of a 3-30 cycles line-to-line fault on line 7-8 of Fig. 10.

Fig. 12. Generator 3 electric power response during successful reclosing of a 3-30 cycles line-to-line fault on line 7-8: (a) triple-pole switching, (b) single-pole switching.
Sherif Omar Faried was born in Cairo, Egypt. He obtained B.Sc. and M.Sc. Degrees in Electrical Engineering from Ain Shams University, Egypt and M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of Saskatchewan, Canada where he is presently a Professor of Electrical Engineering in the Department of Electrical and Computer Engineering. His research interest includes power system dynamics, FACTS, reliability and power quality. He is a Registered Professional Engineer in the Province of Saskatchewan.

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