A new single-pole switching technique for suppressing turbine-generator torsional vibrations and enhancing power stability and continuity

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Abstract: The author presents a new single-pole switching technique for reducing torsional torques in turbine blades and shafts and enhancing power system stability and transmission continuity. During the dead time between single-pole tripping and line reclosing, the significant negative-sequence current flowing into the nearby turbine-generator may cause supersynchronous resonance effect on low pressure turbine blades and even results in fatigue damage. Thus, during this time, the proposed grounding capacitor set up at the neutral of the wye transformer is inserted not only to eliminate this negative current but also to recover the pre-fault power transmission in advance. The induced adverse effect on turbine blades can be precluded. Adaptive reclosing is then applied to reclose the tripped phase and the grounding capacitor is switched off. This effectively improves the power system stability again and prevents further torque amplifications. This scheme is suitable for a single-circuit transmission line and can improve system reliability.

1 Introduction

Based on most of the transmission line faults being single-line to ground and not permanent, the advantages of high-speed 'single-pole' tripping and auto-reclosing of circuit breakers (CBs) on respective lines have been well-documented in numerous research work [1–5]. A significant benefit on improving transient stability is gained, because of less real power fluctuation through only one CB pole switching. However, the persistently substantial negative-sequence currents would be injected into the nearby turbine-generators during the dead time between single-pole clearing and line reclosing. Generally this dead time is within 0.5–1.5 s [1]. Two concerns are then raised. The first is the over-heating on rotor field winding. The second is the induced electromagnetic disturbing torque (E/M torque) with double system-frequency (120 Hz) component, which could excite a supersynchronous resonance (SPSR) effect on the low pressure (LP) final row (L0) or next-to-final (L1) row turbine-generator blades [3, 6]. This may bring about blade torque amplification exceeding its endurable strength and then damage the blade in a short time for an over-delayed reclosing time or an unsuccessful reclosure. Therefore studies show that experience with single-pole switching near large turbine-generators was limited in USA [3].

Solving that problem is the motivation behind the development of our proposed method. During the dead time, the equivalent positive-, negative- and zero-sequence networks are in parallel. Herein, a grounding capacitor at neutral of the step-up transformer is inserted to make series resonance in the zero-sequence network. The net zero-sequence impedance can be nearly short-circuited to bypass both the networks of negative- and positive-sequence. Then adaptive reclosing is applied to reclose the tripped phase and grounding capacitor is switched off. Such a proposed technique has several superiorities as follows:

(1) Due to the positive-sequence network being bypassed just after single-pole tripping, the pre-fault transmission system capacity is restored right away after fault clearing, and not after reclosing. This will greatly improve the system stability.

(2) The neutral grounding thyristor-controlled capacitor is not a resistance, which consumes no real power. Besides this capacitor is not a series one. There is no induced subsynchronous current implying no subsynchronous resonance risk is present.

(3) By using adaptive reclosure for reclosing a line fault, the sustained fault on the faulted phase will be identified. This eliminates the possibility of reclosing an open line conductor into a permanent fault. This eliminates the possible torque amplification in turbine blades and shafts and greatly improves the system stability.

(4) Using only two transmission lines after tripping single-pole CB is able to carry up to the rated power without losing system synchronism, in which relevant present studies have not been investigated yet.

2 System descriptions

2.1 System model

Fig. 1 schematically shows the electromechanical system under investigation. It consists of a turbine generator which is connected via a transformer to an infinite bus system through a double-circuit transmission line. The practical steam turbine unit analysed in this study is a close-coupled and cross-compound reheat unit that operates at a rotational speed of 1800 rpm. The rated capacitor of the
generator, which was installed in 1984, is 951 MW. Each of the LP steam turbines has A and B spindles, and uses the shrunk-on rotor. There are 11 rows of blades in the LP steam turbine.

### 2.2 Blade model

The typical model of a long blade on the mechanical model of the turbine generator is quite complicated. The flexural, axial and torsional modes vibrate in the same direction as the rotation, perpendicular to the rotation direction and in a twist direction, respectively. Among them, the flexural mode has a lower resonant frequency and is usually chosen to investigate the vibration mode shapes of blades for the SPSR investigation. The simulation data are given in Fig. 2. All of the parameters of this system are in the per unit (p.u.) system, based on generator ratings.

### 2.3 Simulation system model

For time-domain simulation investigations, the entire system studied is modelled with the Matlab-Power System Blockset program [7]. The generator is represented by a six-order state-space d-q-0 model. The step-up transformer is represented by lumped model transformers. Each transmission line is modelled by its equivalent R-L lumped parameters. Each network source is treated as an infinite bus represented as an ideal switch which is able to open at the fundamental frequency. Each CB and thyristor are represented as an ideal switch. Transients are included in the T-G model. A mass-damping-spring model is adopted for turbine model representation.

### 3 Principle of the proposed new single-pole switching scheme

#### 3.1 Design of grounding device

The sequence network connection with one conductor open is given in Fig. 3a, which is from the viewpoint between the left side and right side of the fault point. Three sequence networks are connected in parallel. Thus

\[ I_{\text{pos}} + I_{\text{neg}} + I_{\text{zero}} = 0 \]

where \( I_{\text{pos}} \), \( I_{\text{neg}} \) and \( I_{\text{zero}} \) are the positive-, negative- and zero-sequence currents, respectively [8]. Aimed at the studied system shown in Fig. 1 and neglecting resistances, the total impedance of the zero-sequence network is composed of these three reactances in series.

\[ Z_{\text{zero}} = \frac{Z_t + Z_L + 3Z_G}{2} = \frac{X_t + X_L + 3X_G}{2} \]

(2)

In order to eliminate the negative-sequence current, the fundamental method is to force the net zero-sequence impedance \( Z_{\text{zero}} \) to be zero by the series-resonant effect. Therefore \( Z_G \) can be designed as a capacitor reactance of \(-3X_{G1}\) with the quantity of

\[ X_{G1} = \left( \frac{X_t + X_L}{2} \right) \]

(4)

Then the \( X_{G1}, X_{G2} \) of 0.1929, 0.3381 p.u. are, respectively, determined by the cases of studied double- and single-circuit transmission in Fig. 2. The grounding capacitor value can be deduced as shown in Fig. 3b. As a result of the negligible zero-sequence impedance (only resistive), the zero-sequence current is

\[ I_{\text{zero}} \simeq -I_{\text{pos}} \text{ and } I_{\text{neg}} \simeq 0 \]

(5)

Then the negative-sequence current is eliminated. It is emphasised that the positive-sequence network is also bypassed by this negligible zero-sequence impedance. This is similar to the prefault transmission network that only has positive-sequence network. Thus, the transmission power could recover to the prefault one at the instant of inserting this resonant capacitor rather than the subsequent line reclosing. This helps enhance the transient stability.

#### 3.2 Logic for new single-pole switching scheme

In this paper, the identification of the fault type is carried out by the delaying system. The thyristor controlled switches \( T_{G1} \) and \( T_{G2} \) are normally closed. The sequence of operation is given in Table 1.
of proposed switching logic during a line fault is programmed as follows:

(1) When encountering a single-line to ground fault, the CB single-pole switching is allowed, two signals are provided by the relaying system; one for tripping the conductor of faulted line and the other for conducting the T\text{G1} as seen in Fig. 4\text{a}. Then the grounding capacitor is able to be inserted and then restores to the prefault positive transmission circuit. Reconducting the T\text{G1} (bypassing this capacitor) is interlocked with the subsequent reclosing line CBs by using adaptive single-pole reclosing illustrated in the next sub-section.

If inserting the capacitor is within the single-line to ground fault period, the fault current becomes more severe. The blocking time of T\text{G1} is at 1 cycle after fault clearing to avoid the amplification of turbine generator torsional torques.

(2) For the multiple-phase fault, the single-pole switching is not allowed from over-large negative currents. The switching function will be replaced by triple-pole switching and forbids subsequent reclosure. Then the transmission line system becomes single-circuit one and the T\text{G1} is still kept conducted under this condition, as shown in Fig. 5.

In the figure, it is found that following a new single-line to ground fault, the procedure 1 is repeated but T\text{G2} is substituted for T\text{G1}.

3.3 Principle of the adaptive single-pole reclosing coordinated the thyristor-controlled capacitor

Adaptive reclosing of a transmission line is to control the CB’s reclosure sequence and timing based on sensing the specific existing conditions on the transmission line [4, 9, 10]. A key point of such a reclosing, if employed in single-pole reclosing system, can eliminate the possibility of reclosing the tripped conductor into a permanent fault. As illustrated in Figs. 4\text{b} and 5, the existence or non-existence of a sustained fault can be identified by measuring the voltage of the unenergised phase to determine the allowance of reclosure. The sequence of operation during the adaptive single-pole reclosing of a transmission line is as follows:

(1) If the voltage of the unenergised conductor is equal to zero, this indicates a sustained fault. The protective system will block the reclosing of this conductor and bypassing grounding capacitor X\text{G} (reconducting T\text{G}) is aborted.

(2) If the voltage of the unenergised conductor is just a small percentage of the voltage of the energised phases, this means that the fault no longer exists. This open conductor is reclosed and the grounding capacitor X\text{G} is bypassed simultaneously.

4 Frequency domain analysis

It is well-known that the E/M disturbing torque induced by single-line to ground fault consists of the following three components, a unidirectional component (<2 Hz), a system-frequency component and a double system-frequency component which correspond to the generator delivering power swing, the unsymmetrical fault current and the negative-sequence armature current arising from the unbalanced operation, respectively [11]. These three frequency types of E/M disturbing torques are the main excitation sources to stress turbine mechanism, which govern the turbine blade vibration behaviours.

In this paper, the vibration modes of the turbine system have been analysed using the frequency-scanning method. Suppose that the terminal of the generator rotor is a shaker with electromagnetic torque of one per unit, the frequency-scanning inspects the natural frequencies of steam turbines from 0.01 to 140 Hz with an interval of 0.01 Hz. Ten vibration modes are then present in the turbine system according to the response results in Fig. 6.

Aimed at the double-system frequency excitation, the torque response for the B2F blade is about 2.5, whereas that for the LP2R-GEN shaft is minor. It can be deduced that the severe SPSR effect will be excited in blades rather than shafts during sustained power system unbalance operation.

5 Simulation results

5.1 Unsuccessful reclosing

5.1.1 Transient responses analysis: The transient responses of the E/M torque, the turbine generator torsional torques, the negative-sequence current and the zero-sequence current on the secondary winding of the step-up transformer, the capacitor current and voltage and generator rotor angle during unsuccessful reclosing of a 3-59.5-3
cycle’s single-line to ground fault occurred near the CB1 end after 0.1 s are indicated in Fig. 7 for the case of traditional single-pole switching, and in Fig. 8 for the case of the proposed single-pole switching. The negative-sequence current shown in Fig. 7 because of system unbalance during the dead time causes the E/M torque of double-system component in Fig. 7, which induces SPSR torque amplification in Fig. 7. As can be seen from Fig. 8, the proposed single-pole switching restricts the negative-sequence current which completely damps the severe SPSR amplification of blade torsional torque during the dead time. The further torque amplifications during unsuccessful reclosing period (1.1417–1.1917 s) on both shafts and blades are effectively avoided. This is because of the persistence of the line fault being perceived and then the reclosure is aborted. On average, the peak-to-peak torque (the deviation between the maximum and minimum) reduction ratio for all shafts and blades is about 44% as tabulated in the fourth column of Table 1. It is worth noting that the rating current of the grounding capacitor should be more than 3.0 p.u. as demonstrated in Fig. 8 because it is equal to three times of zero-sequence current. The capacitor voltage rating as depicted in Fig. 8 is easily implemented even though it is series-resonant.
5.1.2 Comparison with multiple-phase line faults:
In the past, power accidents occurring as either line-to-line [12, 13] or three-phase-to-ground faults [12, 14] were believed to induce the largest torsional stresses so that they may have been used as a minimum specification in the design appraisal for turbine mechanism. However, the compound blade torsional torque (because of unsuccessful single-pole reclosing) is much higher than that excited by those two types of faults as listed in the last two rows of Table 2. This illustrates that the blades are very likely damaged due to such a line accident. The proposed single-pole switching scheme has successfully reduced the torsional torque to an acceptable level that is less than the torques in the last two rows of the table. The potential possibility for the damage of LP long blades has been excluded.

5.2 Respect of transient stability

From Figs. 7g and 8g, the generator swing deviation for the case of the proposed single-pole switching (24.45°) is much smaller than that corresponding to the traditional single-pole switching (55.26°). This is because the proposed single-pole switching recovers the prefault transmission system capacity just after fault clearing and prevents reclosing into a

Table 1: Peak-to-peak value of the simulation transient responses (p.u.)

<table>
<thead>
<tr>
<th>Case A</th>
<th>Case A</th>
<th>R%</th>
<th>Case B</th>
<th>Case B</th>
<th>R%</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(E/M torque)</td>
<td>4.492</td>
<td>4.474</td>
<td>0.40</td>
<td>4.474</td>
<td>4.474</td>
</tr>
<tr>
<td>T(HP-LP1F)</td>
<td>1.214</td>
<td>0.663</td>
<td>45.40</td>
<td>0.673</td>
<td>0.663</td>
</tr>
<tr>
<td>T(LP1R-LP2F)</td>
<td>2.693</td>
<td>1.899</td>
<td>29.48</td>
<td>1.954</td>
<td>1.899</td>
</tr>
<tr>
<td>T(LP2R-GEN)</td>
<td>5.249</td>
<td>3.237</td>
<td>38.34</td>
<td>3.238</td>
<td>3.237</td>
</tr>
<tr>
<td>T(GEN-REC)</td>
<td>0.145</td>
<td>0.057</td>
<td>60.85</td>
<td>0.081</td>
<td>0.081</td>
</tr>
<tr>
<td>T(B1F)</td>
<td>0.302</td>
<td>0.157</td>
<td>47.93</td>
<td>0.230</td>
<td>0.159</td>
</tr>
<tr>
<td>T(B1R)</td>
<td>0.282</td>
<td>0.150</td>
<td>47.02</td>
<td>0.207</td>
<td>0.156</td>
</tr>
<tr>
<td>T(B2F)</td>
<td>0.563</td>
<td>0.271</td>
<td>51.87</td>
<td>0.344</td>
<td>0.271</td>
</tr>
<tr>
<td>T(B2R)</td>
<td>0.406</td>
<td>0.271</td>
<td>33.26</td>
<td>0.323</td>
<td>0.271</td>
</tr>
<tr>
<td>Rotor angle, deg.</td>
<td>55.257</td>
<td>24.454</td>
<td>55.75</td>
<td>39.204</td>
<td>24.540</td>
</tr>
</tbody>
</table>

*With the traditional single-pole switching
*With the proposed single-pole switching
R%, the improvement percentage

Table 2: The peak-to-peak torque of turbine blades following different line faults (p.u.)

<table>
<thead>
<tr>
<th>Fault type</th>
<th>T(B2F)</th>
<th>T(B2R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsuccessful single-pole reclosing</td>
<td>0.563</td>
<td>0.406</td>
</tr>
<tr>
<td>Unsuccessful single-pole reclosing*</td>
<td>0.271</td>
<td>0.271</td>
</tr>
<tr>
<td>Line-to-line</td>
<td>0.370</td>
<td>0.343</td>
</tr>
<tr>
<td>Three-phase-to-ground</td>
<td>0.388</td>
<td>0.350</td>
</tr>
</tbody>
</table>

*Proposed single-pole switching scheme

Fig. 9 Transient behaviours during successful single-pole reclosing of a 3-59.5 cycle’s single-line to ground fault

a With the traditional single-pole switching
b With the proposed single-pole switching
sustained fault conductor. The less acceleration of the rotor body helps prove the improvement of system stability.

5.3 Successful reclosing

Similarly, the transient responses during successful reclosing of a 3-59.5 cycle’s single-line to ground fault are shown in Fig. 9a for the case of traditional single-pole switching, and in Fig. 9b for the case of the proposed single-pole switching. The reclosure of the tripped conductor and the \( T_{G1} \) is actualised synchronously according to the disappearance of temporary fault being detected. As demonstrated in Fig. 9 and the last column of Table 1, the SPSR effect in turbine blades is eliminated by the proposed technique, whereas the torque reduction in turbine shafts is insensitive to the E/M torque excitation of double-system frequency component. In addition, the stability is also improved.

6 Effect of the single-circuit line

6.1 Transient responses analysis

It is assumed that one of the double-circuit lines in Fig. 1 (e.g. L2) is tripped due to some out-of-service factors. Note that single-circuit line having double net transmission impedance causes the generator to approach boundary stable margin. Thus, adopting higher-speed reclosing is inevitable. However, successful single-pole reclosing depends on complete secondary arc extinction [4]. Fig. 10a represents the studied single-circuit line system has lost synchronism subject to identical single-line to ground fault. In this case, the transmitting power would be out of service by relaying system. Figs. 10b and c clearly demonstrate that the proposed single-pole switching scheme as described in Fig. 5 not only gives considerable improvements on transient stability but also still restricts the SPSR amplifications during successful reclosing or unsuccessful reclosing, respectively. This also proves that, in spite of sustained lack of one-phase operation, the feasibility and effectiveness of the proposed method are still unchanged.

6.2 Respect of transmission reliability

The single-line to ground fault is assumed to occur among all line faults with a probability of 0.9. Assuming that the probability of permanent line fault is 0.6, which leads to an unsuccessful reclosing and tripping three-pole CBs (one-circuit line). Based on the assumption of tripping a one-circuit line subject to multi-phase fault and single-pole

![Fig. 10](image-url) Transient behaviours during successful reclosing of a 3-59.5 cycle’s single-line to ground fault in a single-circuit line system

- Traditional single-pole switching
- Proposed single-pole switching
- Of a 3-59.5-3 cycle’s single-line to ground fault for the proposed single-pole switching
successful reclosing subject to temporary single-line to ground fault, provided that two sequential line faults occurs on different circuit lines, respectively, and independently, the probability of power outage for the case of traditional single-pole switching in studied systems can be written as: 
\[ 0.1 \times (0.9 \times 0.4 + 0.1) + 0.9 \times 0.4 \times (0.9 \times 0.4 + 0.1) = 0.212 \]. Similarly, the probability of outage for the proposed single-pole switching scheme is 
\( 0.1 \times 0.1 = 0.01 \). Thereby, the power outage probability would be reduced to 1/21 times. This helps improve reliability of supplying power and lessen the urgent pressure for line maintenance workers during single-circuit isolation.

7 Conclusions

(1) Applying single-pole switching near large turbine generators is no longer limited because the drawbacks of potential blade SPSR effect and overheating in the field winding for single-pole switching systems have been overcome by the proposed scheme.

(2) Because the instant of restoring transmission power is not line reclosing but fault clearing, the stability is greatly improved and the special purpose of CBs with 'special high-speed reclosing' is accordingly less necessary. In addition the complete deionisation of the fault arc path or the detection for the line fault existence can be guaranteed to provide a high possibility of successful reclosure.

(3) High possibility of successful reclosure is the fact that reduces the occurrence for more severe torque amplification during a unsuccessful reclosure. Blades can be prevented from failure following a permanent single-line to ground fault and their life expectancy is increased again.

(4) Because the single-line to ground fault are the most frequent and maintaining system synchronism only needs two health phase operation by the proposed scheme, improvement to the continuity of supply power can be expected.

(5) In the planning and designing stage, the proposed multiple capacitor grounded banks can be an internally built-in device in a radial single-pole switching transmission line system.

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9 References


