Applying Improved Blocking Filters to the SSR Problem of the Tuoketuo Power System

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***Abstract*—Blocking filters (BFs) were designed to solve subsynchronous resonance (SSR) problems induced by fixed series capacitors (FSCs) of the Tuoketuo transmission system. However, during the commission of BF, unstable self excitation (SE) occurred unexpectedly, resulting in suspension of the project. This paper first analyzes the mechanism of how BF causes SE. Then, the parameters' sensitivity is investigated and the quality factor (Q) of BF reactors is discovered to have opposite impact on SE and torsional interaction (TI). Thus, by appropriately lowering Q of BF reactors with supplemental resistors, an improved BF scheme is put forward to simultaneously mitigate the different types of SSR problems. As a key issue, the determination of supplemental resistors is formulated into a multi-objective optimization problem, which is then effectively solved with our proposed searching method. Finally, the effectiveness of improved BFs is verified with field tests. For the first time, actual measurements of filed tests on BFs are offered. What is more, their comparison with model studies demonstrates a good agreement. This work paves the way for putting both BFs and FSCs into service, thereby ensuring safe operation and transfer-capability enhancement of the system.**

***Index Terms*—Blocking filter, field test, fixed series capacitor, self excitation, subsynchronous resonance, supplemental resistors, torque amplification, torsional interaction .**

NOMENCLATURE

BF	Blocking filter.
FSC	Fixed series capacitor.
HA	Hunyuan—Anding.
HB	Hunyuan—Bazhou.
Q	Quality factor.
SE	Self excitation.
SSR	Subsynchronous resonance.
TA	Torque amplification.
TH	Tuoketuo—Hunyuan.
TI	Torsional interaction.
TPP	Tuoketuo power plant.

I. INTRODUCTION

FIXED series compensation (FSC) is an economic solution to enhance stability and transfer capability of transmission systems. However, a potential problem in series compensated lines connected to turbine generators is subsynchronous resonance (SSR), which could result in failures of the mechanical shaft system if not handled properly [1]–[4]. Therefore, mitigation methods must be applied for a system with the risk of unstable SSR [5]. In history, various measures, including blocking filter (BF) [6]–[8], supplementary excitation damping control [9],[10], static var compensator [11],[12] and thyristor controlled series compensator [13], have been practically used to solve the SSR problem.

In this paper, the SSR issue and its corresponding countermeasure, or the BF scheme, in the Tuoketuo system, is discussed. The Tuoketuo power plant (TPP) has eight 600-MW steam turbine generators connected to North-China Power Grid via 500-kV lines, which are compensated with 40%–45% FSCs. Preliminary studies [13] indicated that the FSCs would result in serous problem of torsional interaction (TI) and torque amplification (TA) [4]. After extensive discussion, the BF scheme was selected to solve the problem. TPP then signed a contract with GE, who was assigned to design and manufacture eight BF equipments. Following the installation, a commission test was conducted on April 12, 2008 on one of the BFs with all FSCs out of service. However, upon insertion of BF, an unexpected self excitation (SE) occurred and caused an accidental outage of the generator. Similar SE phenomenon appeared during the tests of other BFs. As a result, neither BF nor FSC could be put into operation on schedule.

The SE caused by BF was never reported in previous literatures. This paper studied its basic mechanism in three aspects, namely, circuit analysis, eigenvalue computation and nonlinear electromagnetic simulation. The impacts of the parameters of generator, network and BF on SE risk were also investigated. To handle the different types of SSR, an improved BF scheme was proposed, where appropriately designed resistors were added to certain reactor branches of the original BFs. By lowering the quality factor of these reactors, a compromise was achieved between the suppression of TI and the avoidance of SE risk. The key to the improved scheme was to design a set of minimum supplemental resistors that could maximize its blocking effect while simultaneously stabilize SE modes. The task was done

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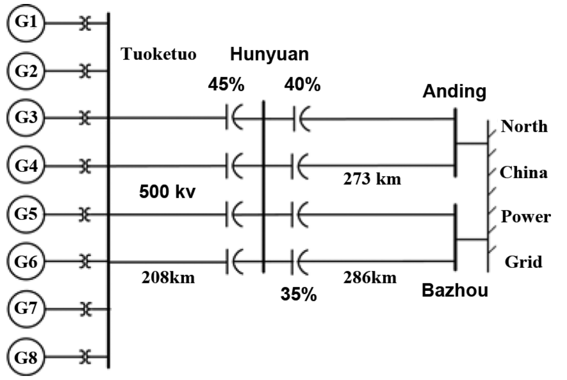


Fig. 1. Single-line diagram of the Tuoketuo transmission system.

with a delicately designed searching algorithm based on eigenvalue analysis. The improved BF scheme was then implemented and finally tested in practice. Its effectiveness was fully verified in both the "on" and "off" status of the FSCs.

The innovation in this work is threefold. First, the reason why BF causes SE is explained and the impacts of BFs' and generators' parameters on SE risk is quantitatively analyzed. Second, an improved BF scheme is put forward to compromise the suppression of different types of SSR, and the parameters of its key components, i.e., the supplemental resistors, are designed in an optimized way. Third, the modified BF scheme is verified through field tests and good agreement is observed between field measurements and simulation results, which confirms the effectiveness of the improved design as well as the correctness of the model study.

The rest of the paper focuses on four aspects of the project, i.e., the BF-induced SE problem (Section II), its mechanism study (Section III), the improved design of BF (Section IV), and the results of the final field tests (Section V).

II. STATEMENT OF THE PROBLEM

A. Description of the Tuoketuo System

The Tuoketuo power plant is located in Inner Mongolia Autonomous Region, about 400 kilometers west of Beijing. It has eight 600-MW turbine-generators connected to North China Power Grid through 500-kV lines. Fig. 1 is the one-line diagram of the equivalent system. To improve transfer capability as well as system stability, FSCs are applied to the Tuoketuo-Hunyuan (TH), Hunyuan-Anding (HA), and Hunyuan-Bazhou (HB) lines with compensation degrees being 45%, 40%, and 35%, respectively.

Among the eight generators, G1-G2 and G3-G8 are, respectively, identical; while the shaft systems of G1-G4 and G5-G8 are, respectively, the same. Each turbine-generator consists of four rotors, i.e., a high-and-intermediate-pressure turbine, two low-pressure turbines, and the generator rotor, resulting in three torsional modes. Their frequencies (in Hz) are 13.0 (mode 1), 24.9 (mode 2), and 29.5 (mode 3) for G1-G4 and 15.1 (mode 1), 26.0 (mode 2), and 30.5 (mode 3) for G5-G8.

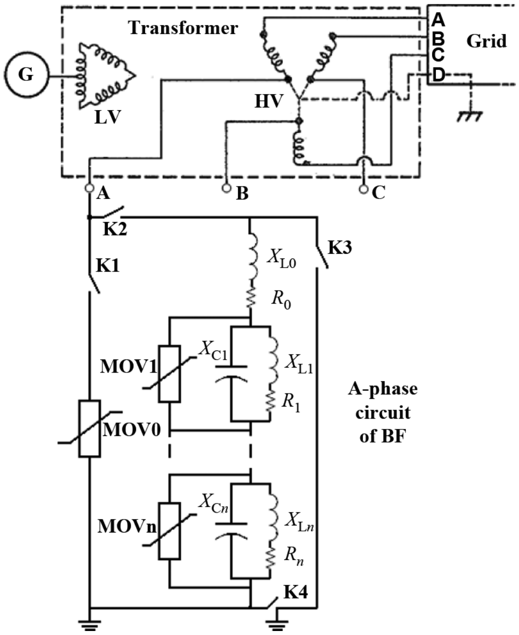


Fig. 2. Circuit diagram of BF and its connection with the transformer.

B. Originally Designed BFs

Since 2005, extensive studies had been done on the SSR issue of TPP. It was concluded that the system would suffer serious TI/TA problem once FSCs were put into service, and that counter-measures must be taken [13]. At the beginning of 2006, TPP decided to adopt BF as the solution and chose GE to design and manufacture the eight BF equipments.

The circuit of BF is shown in Fig. 2[6]–[8]. It is a three-phase passive circuit, installed from the low-voltage end of main step-up transformer high-side winding to the grounding neutral point. Each phase of BF has n stages, where n denotes the number of torsional modes to be blocked. Each stage is a parallel resonant circuit, composed of capacitors, reactors and resistors. Metal oxide varistors or MOVs are used as voltage limiting device to protect the circuit components.

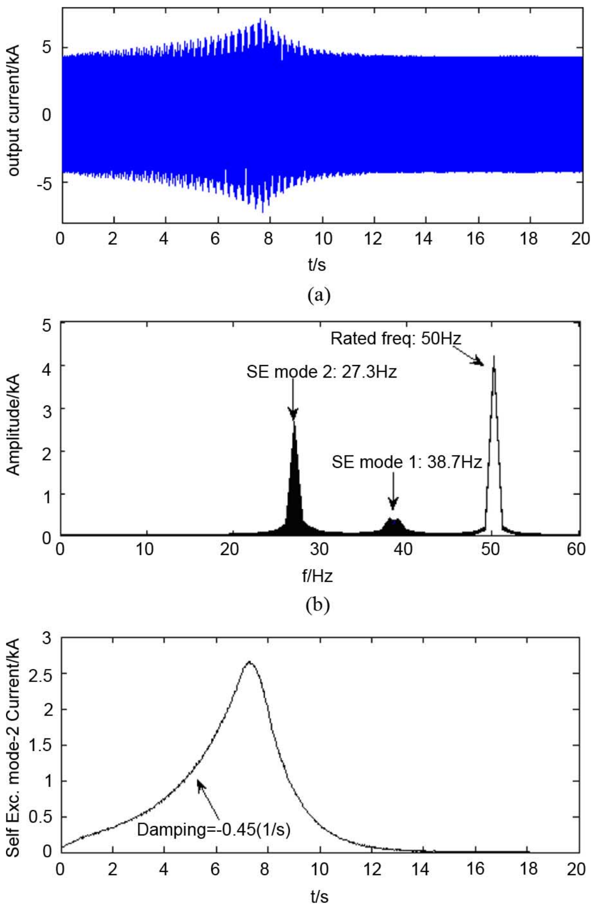
GE designed two types of BF. The first type for units 1 to 4 has two stages, corresponding to torsional modes 1 and 2; while the second type for units 5 to 8 has three stages, corresponding to modes 1, 2 and 3. Each type has the same parameters, the measured values of which are listed as follows:

G1-G4: $X_{\rm L0} = 24.053\ \Omega$, $R_0 = 0.24053\ \Omega$, $X_{\rm L1} = 3.5539\ \Omega$, $R_1 = 0.01966\ \Omega$, $X_{\rm C1} = 2.1520\ \Omega$, $X_{\rm L2} = 57.6308\ \Omega$, $R_2 = 0.2887\ \Omega$, $X_{\rm C2} = 14.8766\ \Omega$;

G5-G8: $X_{\rm L0} = 28.250\ \Omega$, $R_0 = 0.2825\ \Omega$, $X_{\rm L1} = 10.3143\ \Omega$, $R_1 = 0.04941\ \Omega$, $X_{\rm C1} = 5.7616\ \Omega$, $X_{\rm L2} = 42.2872\ \Omega$, $R_2 = 0.19906\ \Omega$, $X_{\rm C2} = 9.9648\ \Omega$, $X_{\rm L3} = 23.4565\ \Omega$, $R_3 = 0.1170\ \Omega$, $X_{\rm C3} = 3.9407\ \Omega$.

C. SE Problem Caused by the Original BF

After the installation of BFs, on April 12, 2008, the commission test was first carried out on the BF of unit 1 with all FSCs out of service. However, when the BF was switched on, the current of unit 1 rose sharply and its waveform was seriously distorted. Meanwhile, a strong vibration of the tested unit was



(a)

(b)

(c)

Fig. 3. SE phenomenon that occurred during the first operation of BF at unit 8.

felt and heard. Soon the generator was tripped and the test suspended. At that time, the phenomenon observed was far beyond the expectation of the project team. Post hoc analysis showed that serious SE was induced by the BF during the test. Similar SE appeared again during later experiments on other BFs. As a result, neither BF nor FSC could be put into practical operation on schedule.

Here, the test result of unit 8 is used to analyze the BF-induced SE. The operation condition was as follows: six units (without units 3 and 7) were on line; the power output of unit 8 was 110 MW while those of other units ranged from 400–600 MW; all transmissions were in service, though without any FSC in operation. Upon the switch-on of the BF, the current of unit 8 increased gradually with distorted waveform, or a diverging SE was observed. Then the BF was manually switched off and the SE phenomenon died out immediately. Fig. 3 depicts the instantaneous phase-A current and its frequency spectrum, wherein two SE modes can be seen clearly. Their frequencies are 27.4 Hz (SE mode 2) and 38.7 Hz (SE mode 1), corresponding to the 2nd and 1st stages of BF, respectively. The amplitude of SE mode 2 is shown in Fig. 3(c), which demonstrates the development and attenuation process of SE during the switch-on/off operations of the BF.

D. Different Types of SSR and Our Proposed Solution

BFs were adopted to restrain TI and TA. However, they caused another type of SSR, i.e., SE, which had never been reported in previous applications. Thus, the question, why BFs cause SE, became the focus of the project. To find the reason, researchers from GE and China conducted thorough simulation analysis on the system model. The results indicated that SE would not appear when using the original generator parameters. However, it did appear as some of the parameters deviated from the given values for the initial design. In other words, SE is very sensitive to generator parameters.

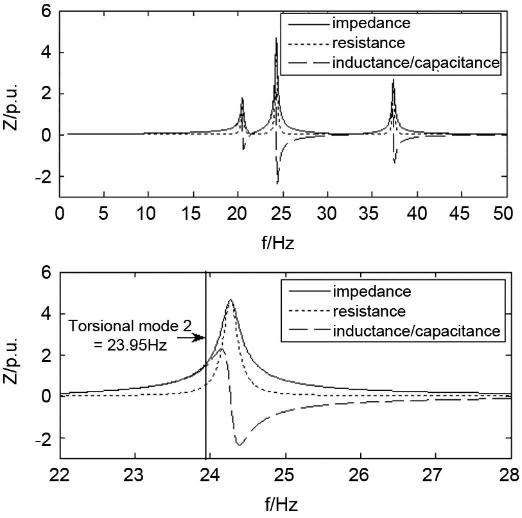


Fig. 4. Impedance-frequency characteristic of BF.

Therefore, in order to put BFs and FSCs into operation, different types of SSR, i.e., TI, TA, and SE, must be handled. Our proposed solution is as follows: First, identify the exact parameters of each generator. Second, investigate the mechanism of BF-induced SE and the impact of system parameters on SE. Third, improve the BF design for simultaneous suppressing the different types of SSR. Then, modify the original BFs when necessary. Finally, validate the improvement through field tests.

III. Mechanism Study of the BF-Induced SE

A. Circuit Analysis

Use the BF of unit 8 to analyze the circuit principle of SE. Its impedance-frequency characteristic is plotted in Fig. 4. Obviously, the impedance is a nonlinear function of frequency. The three-stage BF has three parallel resonance points, the frequencies of which are slightly higher than the complementary frequencies of corresponding torsional modes. BF has very high impedance at complementary torsional frequencies and thus can restrain the current of those frequencies. Consequently, the electrical damping of torsional modes is improved and the transient torque can be reduced. This is the basic principle of using BF for mitigating SSR.

However, BF exhibits very high capacitance and very small resistance at frequencies a little higher than the resonance points. This is the underlying reason why BF causes SE. The equivalent circuit of the BF in series with the generator and the grid is shown in Fig. 5(a) and its impedance versus frequency characteristics is depicted in Fig. 5(b). Three series resonance points can be observed, where the resistances are very small. Since the series resonant frequencies are subsynchronous, the

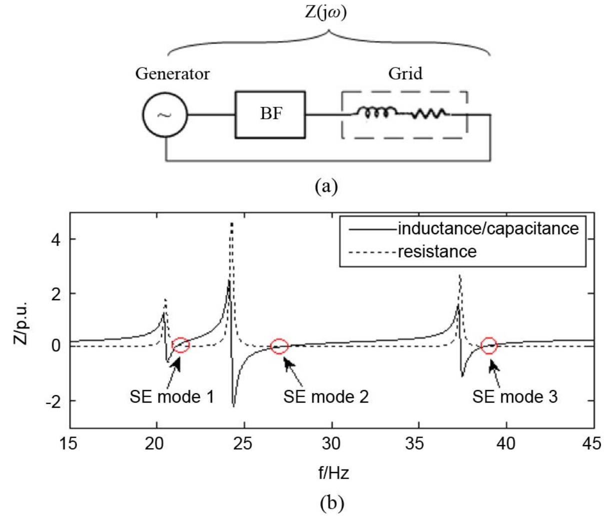


Fig. 5. Equivalent circuit of the whole system including the BF and its impedance-frequency characteristic.

unit behaves as an induction motor with negative slips, or an induction generator, at these frequencies. So, once the total resistance of the armature side is not enough to overcome the negative apparent resistance of the "induction generator", SE modes become unstable. With the real parameters considered, the series resonant points, or SE modes, can be located, with their frequencies at the stator side being 38.7 Hz, 27.4 Hz, and 21.2 Hz, corresponding to the three stages of BF, respectively.

To sum up, the above analysis explained the circuit mechanism of SE: BF is nonlinear impedance in the frequency domain. It appears as a large reactance with strong damping (high resistance) below and close to the parallel resonant frequency, and thus can inhibit the torsional vibration. However, above and close to the parallel resonant frequency, it behaves as a less-damped (low resistance) capacitance, which is prone to "match" the parameters of generator and grid to form series resonance. Further, if the total damping or equivalent resistance at the series resonant frequencies is less than zero, SE would occur.

B. Eigenvalue Analysis

Circuit analysis helps to understand the physical mechanism. However, it cannot quantify the stability or identify risky conditions of SE modes. So, the eigenvalue method is adopted to further analyze its characteristics and parameter sensitivity.

Either TI or SE can be viewed as a stability phenomenon of the linearized system model [14], [15]. In other words, their stability and parameter sensitivity can be investigated with the eigenvalues of the small-signal model obtained at a certain working point [15]. In our study, a detailed linearized system model of the Tuoketuo transmission system (including the BFs) is developed, in which the generator is represented with the dq0 model with three damper windings [16], [17] and the static self-parallel excitation system is modeled with the modified IEEE ST4B-type AVR and PSS2B-type PSS [18]. Then the eigenvalues are calculated and the corresponding TI and SE modes are picked out. As an example, Table I lists the TI and SE modes for the operation scenario of the field test mentioned in Section II. Without BF, unit 8 has three stable TI modes (because FSCs were out of service); when its BF was put into operation, three SE modes appeared, their frequencies being around 11.3 Hz (SE mode 1), 22.6 Hz (SE mode 2), and 28.8 Hz (SE mode 3), corresponding to the stage 1, 2, and 3 circuit of the BF, respectively. When viewed from the stator side, the SE modes are reflected in some variable, for instance, the current, with the complementary frequencies (38.7, 27.4, and 21.2 Hz). For the studied case, the real parts of SE modes 1 and 2 are positive, indicating they are unstable and will cause divergent SE phenomenon. This result of eigenvalue analysis is consistent with the previous circuit analysis.

TABLE I
EIGENVALUES CORRESPONDING TO THE TI AND SE MODES OF UNIT 8

	$\lambda/2\pi$（Without BF）	$\lambda/2\pi$（with BF of unit 8）
TI mode	-0.0084 + j30.5222 -0.0092 + j26.0808 -0.0215 + j15.2664	-0.0090 + j30.5203 -0.0108 + j26.0519 -0.0222 + j15.2591
SE mode	/	-0.1099 + j28.8287 **0.0712 + j22.6245** **0.0324 + j11.2858**

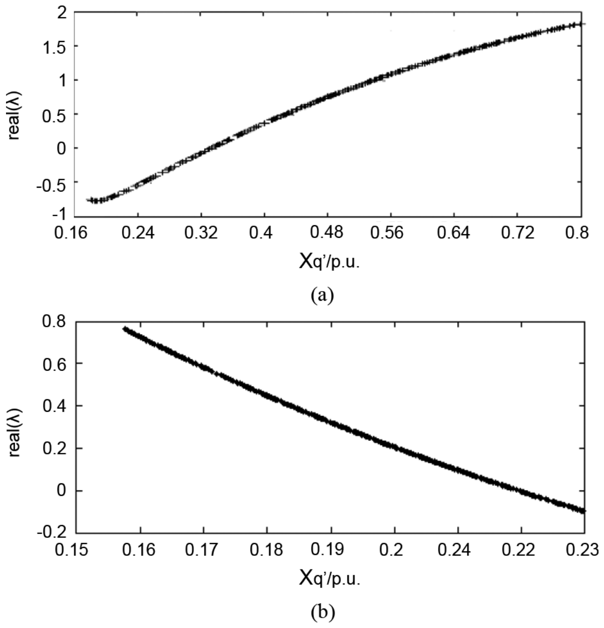


Fig. 6. Relationship between SE mode 2 and Xq' and Xd" of unit 8.

By eigenvalue analysis, the relationship between the real part of SE mode 2 and the transient and sub-transient reactance Xq' & Xd" of unit 8 and the quality factor (Q) of the BF reactor is investigated. Typical results are shown in Figs. 6 and 7. It is observed that Xq', Xd", and Q have significant impact on SE dynamics. Similar analysis indicates that a number of other parameters of the generator and the BF parameters have influence on the characteristics of SE. So, if these parameters are not accurately given, or their diversity not considered, the designed BF may lead to unstable SE phenomenon. This is probably the reason why the originally designed BFs caused the unexpected SE problem during their commission tests. The sensitivity analyses also show that it is possible to eliminate the SE risk by adjusting the quality factor of the BF reactors.

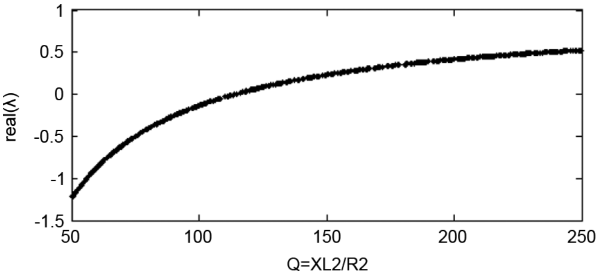
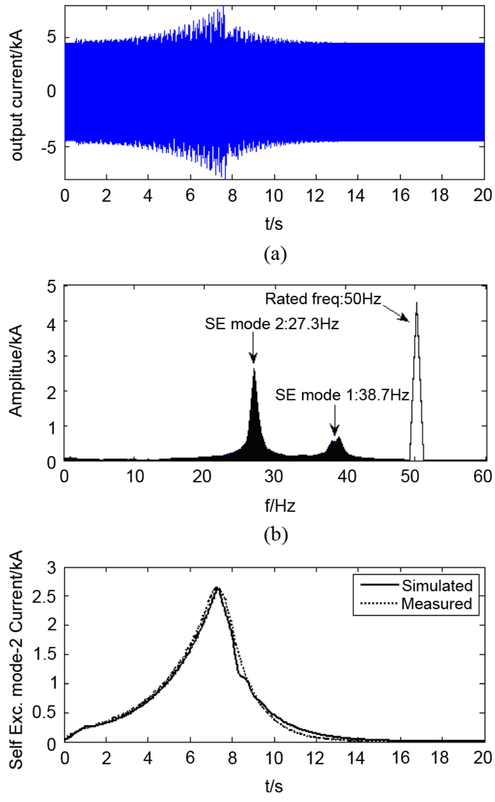


Fig. 7. Relationship between SE mode 2 and the Q value of the BF.



(a)

(b)

(c)

Fig. 8. Simulation of the SE occurred during the operation test of BF at unit 8.

C. Electromagnetic Simulation Versus Field Test

A detailed electromagnetic model of the Tuoketuo system including BFs and FSCs is established in PSCAD/EMTDC for time-domain simulation. The above-mentioned commission test on the BF of unit 8 is simulated and the results are illustrated in Fig. 8. When compared with Fig. 3, it can be seen that the simulation study agrees well with the field test.

IV. Improved Design of BF

A. Basic Idea of Improving BF Design

Each stage of BF circuit has three key elements: the capacitor (C), the reactor (L) and its quality factor (Q), or the resistance (R) of the reactor branch. To suppress a specific TI mode, L and C must satisfy the following resonant condition:

$$\begin{aligned} f_{\mathrm{r}} &= \frac{1}{(2\pi\sqrt{LC})} \\ &= (f_0 - f_{\mathrm{TI}}) + \Delta f, \quad \Delta f = 1 \sim 2\ \mathrm{Hz} \end{aligned} \tag{1}$$

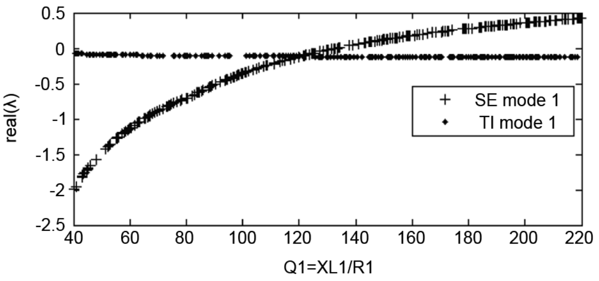


Fig. 9. Relationship between TI and SE modes and Q of BF reactor (unit 8).

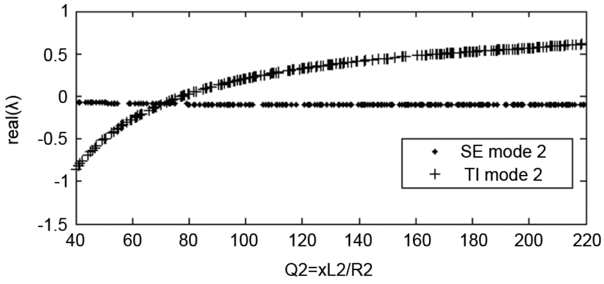


Fig. 10. Relationship between TI and SE modes and Q of BF reactor (unit 8).

where f_{r}, f_0, and f_{T1} represent the resonant frequency of BF, system frequency, and the torsional frequency, respectively.

Therefore, each stage of BF circuit has only two parameters to be freely adjusted, namely, L (or C) and R (or Q). Here, the quality factor (Q) of the reactor is defined as

$$\mathrm{Q} = \frac{2\pi f_0 L}{R}. \tag{2}$$

Since BFs had already been manufactured, installed, and their reactors have very limited tap options, it is impossible to make wide-range adjustments to the reactor (L). The previous analysis (see Fig. 7) shows that increasing the resistance of the reactor or lowering its quality factor helps to reduce the SE risk. What is more, just adding some resistors to the BF circuit is much less costly and easy to implement in engineering.

The impact of Q on the stability of TI and SE modes is simultaneously analyzed using the eigenvalue method. Figs. 9 and 10 show the typical results. It can be seen that the change in Q has opposite effects on TI and SE dynamics. A decrement of Q helps to stabilize SE modes. However, the higher the value of Q, the better blocking effect can be achieved to restrain torsional vibration. From Figs. 9 and 10, the key observation is that: when Q alters in the range of $50 \sim 200$, real parts of SE modes change considerably, from negative to positive; however, the variation of TI modes is very small. Therefore, it is possible to handle the SE and TI problems simultaneously by adding appropriate resistors to some reactors of the BFs.

B. Optimal Design of the Supplemental Resistors

In designing the supplemental resistors, the following goals should be taken into account: i) stabilizing all SE modes to ensure safe operation of BF; ii) enhancing the damping of torsional modes for effective mitigation of SSR induced by FSCs; iii) reducing the transient torque and fatigue loss-of-life of turbine generators caused by serious faults; iv) lowering the investment cost, operational loss and maintenance charge of the supplemental resistors. Further, the diversity of operation conditions and system disturbances as well as the interaction of multiple generators and BFs must be considered. Thus, determination of the supplemental resistors is a multi-objective, high-dimension robust optimization problem, to which, we proposed an effective method, including the following steps:

1) Defining the "evaluation scenarios". To evaluate the effectiveness of the improved BF scheme in practice, about 110 thousand operating conditions are selected to form the set of "evaluation scenarios". While these evaluation conditions by no means limit the situations under which the power plant operates, they do bound the range of system operations where the designing of supplemental resistors is relevant.
2) Setting the minimum damping requirement of SE modes. In order to avoid the risk of SE, real parts of the eigenvalue corresponding to SE modes must not be higher than -0.05.
3) Determining the parameters to be optimized and their variation limits. Field tests indicate that only SE mode 2 of units 1 to 4, and SE mode 1 and 2 of units 5 to 8 are at risk of instability. Supplemental resistors are required for these unstable SE modes. Considering that the BFs of unit 1 to 4 and 5 to 8 are, respectively, the same, only three types of supplemental resistors should be designed. Based on previous study and manufacturing possibility, the variation scopes of the three types of resistor are set in the range of 0.10 to $1.50\ \Omega$, 0.10 to $0.10\ \Omega$, and 0.05 to $0.80\ \Omega$ for SE mode 2 of units 1 to 4, and SE modes 1 and 2 of units 5 to 8, respectively.
4) Optimal searching of supplemental resistors. This is a multiple-step trial procedure. For each step, the SE and TI modes are calculated, their stability margins and changing trends analyzed. Then, based on their sensitivity to the change of parameter, a new searching direction is constructed and the supplemental resistors are updated. The trial procedure is continued until a minimum set of supplemental resistors are found, which can make all SE modes meet the stability requirement under all the pre-defined "evaluation scenarios".

Stabilizing all SE modes is the premise of putting BF into operation, which is, in turn, the pre-condition of using it for blocking FSC-induced SSR problem. So the improved design of BF is essentially to find a set of minimum supplemental resistors, which can get rid of the SE risk, and at the same time, keep the Q value of the BF reactors as high as possible in order that the original function of BFs for blocking TI- and TA-type of SSR is reserved to its maximum.

The designed supplemental resistances are shown in Table II. Five tap options are set up for possible adjustment in the future. It should be noted that these resistors cause additional steady-state losses. For instance, the $0.71\ \Omega$, $0.03\ \Omega$, and $0.34\ \Omega$ resistors consume about 122-kW, 68-kW, and 46-kW power, respectively, when the generator is fully loaded.

The eigenvalues corresponding to TI and SE modes under all evaluation conditions are plotted in Fig. 11, where the deep and the light colors denote the original and the improved BF, respectively. It can be clearly observed that: after modification, SE modes change a lot, all moved to the left-hand plane, which means SE risk is completely avoided; while TI modes get very small changes, retaining negative real parts. However, they are very close to the imaginary axis, meaning they have very limited stability margin under some operating conditions.

TABLE II
RESISTORS ADDED TO THE BF CIRCUIT

Unit	Stage 1 resistor / Ω	Stage 2 resistor / Ω
1～4	/	0.71 ± 2×0.1
5～8	0.03 ± 2×0.01	0.34 ± 2×0.05

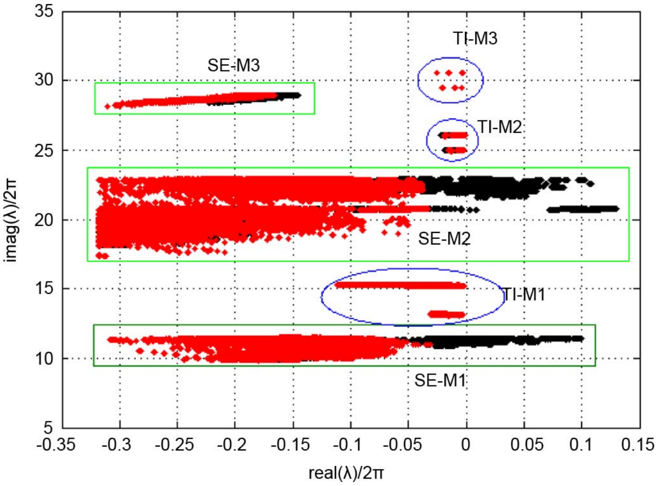


Fig. 11. Scatter plot of SE and TI modes with original and modified BF (light color—modified BF; deep color—original BF).

V. FIELD TESTS OF IMPROVED BFS AND COMPARISON WITH SIMULATION STUDIES

The manufacture and installation of supplemental resistors was completed at the end of 2009. The improved BFs were then tested one by one without FSCs in service during April 14–15, 2010. No unstable SE appeared again. Thus, all BFs were put into operation successfully. To further validate their effectiveness for simultaneous mitigation of the different types of SSR, the project team conducted a series of joint tests on the modified BFs and the series-compensated system during November 29–30, 2010. By planned operations of BFs, generators, FSCs, transmission lines and man-made short-circuit, the dynamic characteristics of SSR were fully investigated. Also, the actual measurements were compared with the results of theoretical analysis and simulation studies.

Here we focus on the joint field test during which seven units (1 to 4 and 6 to 8) were on line and their power output ranged from 300 to 550 MW. Just before the field test, the BFs of online units and all transmission lines were in service. The FSCs were ready to be put into operation.

A. Main Content of the Joint Field Test

The joint field test included the following operations:

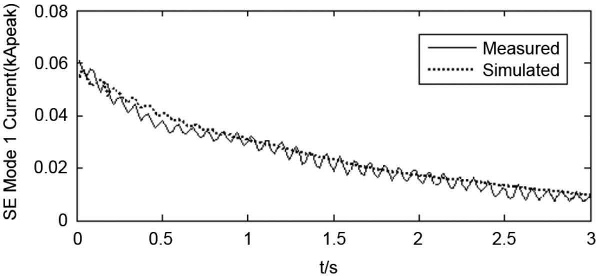


Fig. 12. Comparison of measured and simulated dynamics of SE mode 1 during the switch-on of FSCs (unit 8).

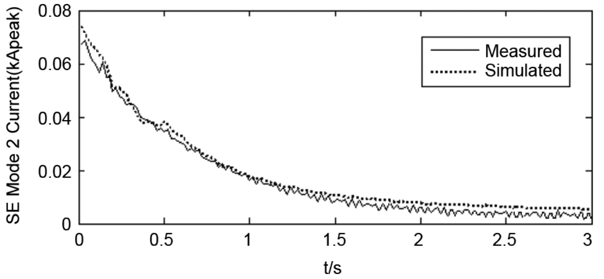


Fig. 13. Comparison of measured and simulated dynamics of SE mode 2 during the switch-on of FSCs (unit 8).

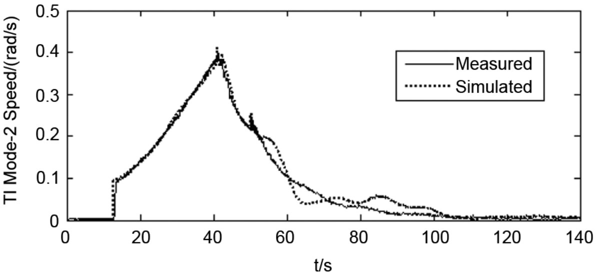


Fig. 14. Comparison of measured and simulated dynamics of TI mode 2 during the switching operations of the FSC of TY line II (unit 1).

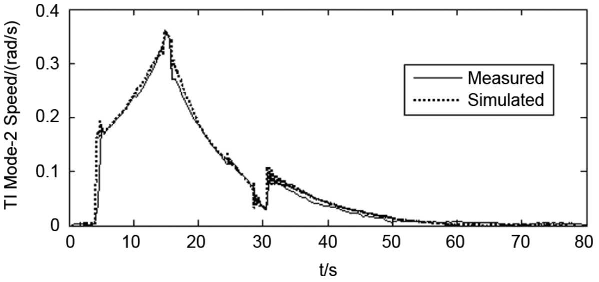


Fig. 15. Comparison of measured and simulated dynamics of TI mode 2 during the switching operations of TY line IV (unit 8).

1) One-by-one switching-on of FSCs to examine the dynamics of TI and SE modes.
2) Tripping and reclosing of TH line IV when some BFs were suspended under different status of FSC. These kinds of operations, according to pre-analysis, may cause unstable TI-SSR. The tests are meant to check the effectiveness of modified BFs in damping TI-SSR.
3) A man-made single-phase-to-ground short-circuit fault was triggered at the far end of TH lines to check the stability of SE and TI as well as to examine the response of the torsional stress relay (protection) when the system was confronted with serious disturbances.

B. *Typical Results of the Field Test*

During the two-day test, more than 41 kinds of topologies of the system and BFs were checked and, SE modes converged quickly under all the tested conditions. TI-SSR was stable if the BFs of online units were in service. Only in two cases, when some of the BFs were disconnected, did TI-SSR diverge. Some typical test results are illustrated as follows.

1) SE dynamics during switch-on of FSCs
   During the test, the eight FSCs were switched on successively. The generator currents were closely watched and recorded. Their spectrum was later analyzed and the SE modes extracted. Figs. 12 and 13 illustrate the dynamics of SE modes 1 and 2 of unit 8 following the switch-on of the last FSC. The field test result is compared with electromagnetic simulation and a good consistency is observed. It validates the effectiveness of the improved BF scheme in avoiding the risk of SE as well as the correctness of the model study.
2) TI-SSR dynamics during the disconnecting and re-connecting operations of BFs

Throughout the test, TI-SSR was well stabilized if BFs were in operation. In order to validate the effectiveness of the modified BFs in damping FSC-induced SSR, some BFs were disconnected deliberately within a short time to trigger diverging TI-SSR, and were then re-connected to check their ability to depress the stimulated SSR.

One of the unstable TI-SSR cases was triggered as: Initially all BFs were in service and only the FSCs of TH lines I to III were switched on. The test procedure included disconnecting the BF of unit 1 first and then bypassing the FSC of TH line II. Immediately, TI mode 2 of unit 1 diverged. After about 30 s, the BF and the FSC were restored so that the TI mode 2 of unit 1 was successfully depressed.

Another unstable TI-SSR case was triggered similarly: Initially all BFs and FSCs were in service. Then the BFs of unit 6 and 7, and the phase-A BF circuit of unit 8 were disconnected. Next, TH line IV was tripped. Immediately, TI mode 2 of unit 6 to 8 was observed to diverge. After about 13 s, the BFs and TH line IV were restored so that TI mode 2 of unit 6 to 8 converged rapidly.

For the above mentioned two cases, Figs. 14 and 15 depict the dynamics of the concerned TI mode 2 and its comparison with simulation results. It is obvious that the improved BFs can damp SSR effectively and the actual response of the system agrees well with the model studies.

C. *Response to the Manual Short-Circuit Fault*

Both the TI and SE modes were damped out immediately following the manual short-circuit fault. For instance, the TI mode-2 speed of unit 8 reached a maximum value of 0.43 rad/s during the fault. But it decayed to nearly zero within 20 s. The torsional stress relay was initiated to accumulate the fatigue loss-of-life, which, however, was too small (less than 0.1%) to trip the generator.

D. Engineering Evaluation of the Improved BFs

The field tests, on one hand, validated the effectiveness of the modified BFs in solving the different types of SSR problems under various system conditions and, on the other hand, verified the correctness of the method and model adopted in this study. After the field test, eigenvalue analysis and electromagnetic simulation were used again to re-evaluate the improved scheme under other operation situations. considering that the performance of BF greatly depends on the parameters of its own and the system, various detuning conditions, for instance, ambient temperature (ranging from $-40^{\circ}\mathrm{C}$ to $+40^{\circ}\mathrm{C}$), off-nominal grid frequency (± 0.2 Hz), and capacitor can failure (one capacitor can failure in each filter stage of each online unit) were taken into account during the engineering evaluation. The results show that the modified BF scheme is able to solve the SE problem under all conditions. However, since the blocking effect is weakened by the supplemental resistors, it may be not robust enough to handle the TI and TA problems under the following two extreme circumstances, for which remedial measures should be taken.

1) In extreme climatic conditions (above $40^{\circ}\mathrm{C}$ or below $-40^{\circ}\mathrm{C}$), BF circuit parameters may deviate too much from the designed value and serious detuning could happen, which could possibly result in unstable TI-SSR under some operation conditions. To solve the special problem, dispatch measures should be taken to actively avoid those risky operation situations, which are identified beforehand.
2) If a single-phase permanent fault occurs on one TY line and close to the power plant, excessive transient torque or fatigue loss-of-life may cause damage to turbine generators due to the repeated fault attack. Then the reclosing logic of TY lines is changed from the traditional pattern, i.e., restoring the circuit after adjustable time delays, to a smarter one, which initiates the reclosing action only after it detects successful re-synchronizing of the other end of the faulted line. Hence, the impact of reclosing onto permanent fault is reduced significantly. Transient torque is lowered to a great extent and the fatigue loss-of-life of shafts can be limited to a tolerable value, for instance, below 5%.

To sum up, a comprehensive engineering evaluation indicates that the improved BF scheme, combined with the above-mentioned remedial measures, can handle the different types of SSR effectively.

VI. Conclusions

In this paper, the improved BF scheme of Tuoketuo Power Plant is applied to handle the different types of SSR problem simultaneously. Some conclusions are drawn as follows:

1) The nonlinearity of BF impedance in frequency domain is the underlying reason for its induced SE. Above and close to the parallel resonant frequency, BF behaves as a less-damped (low resistance) capacitance which, if matched with the system parameters to form a series resonance with negative equivalent resistance, would lead to unstable SE.
2) The stability of BF-induced SE modes is sensitive to the parameters of the BF and the generator. For the Tuoketuo system, unstable SE would not appear in the simulations when using the original generator parameters provided by the manufacturer in its initial design. Testing after the first SE phenomena resulted in a more accurate generator model, which laid a solid foundation for the improved design of BF.
3) The quality factor (Q) of the BF reactors has opposite impacts on TI and SE. A decrement of Q helps to stabilize SE modes, but undermines the blocking effect to torsional vibration. Thus, by appropriately lowering Q of reactors at certain stages of BF circuit with supplemental resistors, an improved BF scheme is proposed for simultaneous mitigation of SE and TI. This solution does not require any modification of the filter reactors and capacitors.
4) The improved designing of BF is essentially to find a set of minimum supplemental resistors to get rid of the SE risk while, at the same time, keep the Q value of the BF reactors as high as possible so that its original function of blocking TI- and TA- types of SSR is reserved to its maximum. The determination of supplemental resistors is formulated into a multi-objective robust optimization problem, which is then effectively solved with our proposed searching method.
5) The effectiveness of the improved BF scheme has been verified with field tests under various operation conditions. What is more, the actual measurements are compared with the results of model study and a good agreement is observed between them, which confirms the correctness of this study.

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