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8TH SOUTHERN AFRICA
REGIONAL CONFERENCE

14 - 17 NOVEMBER 2017

**Electricity Supply to Africa and Developing Economies –
Challenges and Opportunities**

Technology solutions and innovations for developing economies

Use of Thyristor Controlled Series Capacitors (TCSCs) to enhance power system transient stability and their possible application on transmission grids of developing economies

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Most transmission grids are characterised by long transmission lines due to the geographical dispersion of generation sources, which are located far from load centres. Integration of remote generation is often constrained by power system stability limits due to transmission distance. Rotor angle stability (in particular, transient stability) is problematic in most cases.

This paper demonstrates that Thyristor Controlled Series Capacitors (TCSCs) can improve stability when applied on long transmission lines to integrate generators. A case study was conducted for an application on long transmission lines connecting bulk thermal generators in the northern part of South Africa to load centres located hundreds of kilometres away. This paper motivates for due consideration of TCSCs amongst a suite of transient stability improvement tools. TCSCs offer a unique possibility to apply higher degrees of series compensation in networks where there is risk of Sub-Synchronous Resonance (SSR) between the transmission system and thermal generators. Previously, due to SSR risk in such networks, series compensation was avoided or limited to compensation levels lower than required by the system.

The investigation, conducted using PSS/E (Power System Software for Engineers), demonstrated that use of TCSCs is a technically viable and cost effective alternative. Where incremental generation is proposed for an existing pool this solution can offer less impact on the environment compared to building additional lines.

Key Words: *Thyristor controlled series capacitor, transient stability, environmental impact, cost effective solution, Sub-Synchronous Resonance.*

1. Introduction

Long transmission lines characterise power systems with generation sources that are located far from load centres. This is mostly true in developing countries where conventional generation sources (fossil fuel and hydro) are still dominant. While the global trend is to migrate to dispersed renewable energy technologies, a strong case still exists for cost effective bulk generation in remote regions.

System integration of remote generation sources is often constrained by rotor angle instability. Traditional solutions to rotor angle instability (in particular transient stability) include building additional transmission lines, with undesirable consequences for countries faced with financial and environmental constraints. Servitudes acquisition for transmission lines is increasingly difficult; often challenged by environmental conservation groups.

This case study considered part of the South African (SA) transmission network where generation stations are situated long distances away from load centres. Generation stations are being developed in this area due to availability of large coal deposits.

Figure 1 depicts the SA transmission network connecting remote generation sources to load centres, with the study area indicated in the dotted square. Generation evacuation from the study area is constrained from a transient stability perspective.

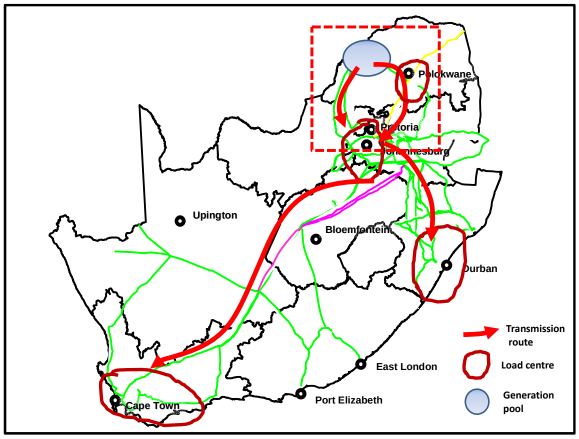

Figure 1 : Network topology [1]

Power system analysis was conducted using PSS®E software, which has time-domain capability. The TCSC was tested on various lines connected to the northern power pool and relevant system disturbances were simulated to determine the impact of TCSC action on rotor-angle stability.

The investigation was conducted to achieve the following objectives:

- Determine transient stability margins with and without TCSC;
- Select the transmission line with most benefit from TCSC application;
- Vary the degree of compensation on the selected line and establish the effect on stability margins; and
- Compare use of a TCSC to addition of a new line that results in the largest stability margins.

2. Review of TCSC Characteristics

A TCSC consists of a series capacitor connected in parallel with a thyristor controlled reactor (TCR). The reactor is controlled by anti-parallel thyristors. Figure 2 depicts the basic circuit of a TCSC [2].

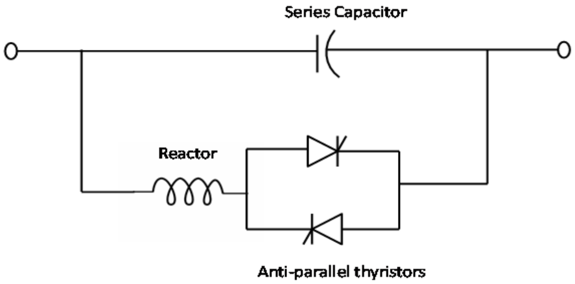

Figure 2 : Basic circuit of a TCSC

The variable impedance of the TCSC is achieved by changing the inductive reactance of the TCR in parallel with the fixed capacitor. The inductive reactance is varied by the firing angle of the thyristors.

2.1. Operation of a TCSC

Figure 3 shows the operating regions of the TCSC. The thyristor in the TCR module is triggered once per cycle and has a conduction interval that is shorter than half the rated power frequency cycle. The TCSC should be operated in the inductive and capacitive regions and must not be operated close to resonance (shaded region) [2]. Resonance occurs when $X_{TCR}(\alpha) = X_C$.

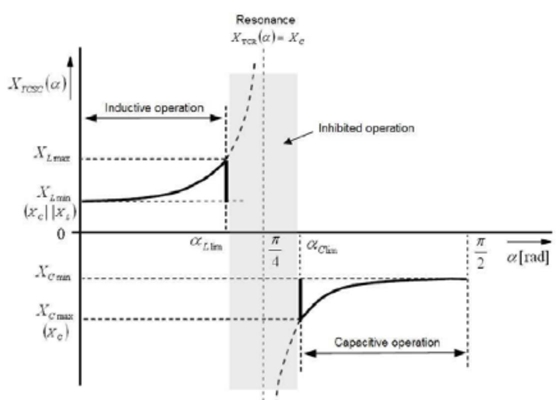

Figure 3 : TCSC operating regions [2]

When thyristors are conducting, the effective capacitive reactance is given by expression [3]:

$$X_{TCSC}(\alpha) = -\frac{X_C X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C}$$

2.2. Modes of operation

In **blocked mode** of operation the thyristors are not conducting and the TCSC operates in fixed capacitor mode, $X_{TCSC} = - X_C$. [4].

In **bypassed mode,** the thyristors are gated so that they are always conducting and most of the line current will flow through the TCR. The series capacitor is essentially bypassed.

In **inductive mode,** the thyristors are gated in the region that allows conduction for part of the cycle; for this firing angle, $X_{TCR} < X_C$, thus X_{TCSC} is positive and the T_{TCSC} exhibits an inductive effect [4].

In **capacitive mode,** the thyristors are fired in the region that allows conduction for part of the cycle; and for this firing angle, $X_{TCR} > X_C$. X_{TCSC} is negative and the T_{TCSC} exhibits a capacitive effect. [4]

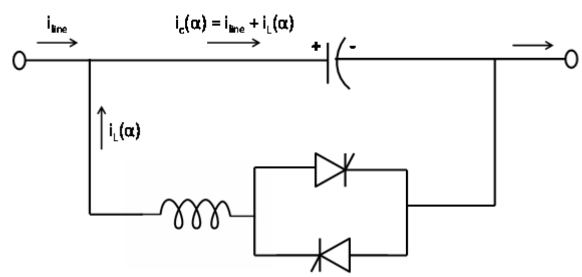

Figure 4 : Capacitive mode of operation

In capacitive mode system transient stability is enhanced. Seen from the power system, a TCSC is viewed as a controllable capacitive reactance in series with a transmission line.

3. Impact on transient stability

A TCSC has an ability to quickly boost its degree of compensation, making it very useful as a solution for improving system post-contingency recovery of the system. The degree of line compensation provided by a series capacitor can be increased temporarily following a network contingency, thereby adding to the dynamic stability of the network (voltage and angular) precisely when it is needed. [5]

The impact of a TCSC on transient stability is illustrated in this section. Figure 5 shows a transmission line equipped with a TCSC.

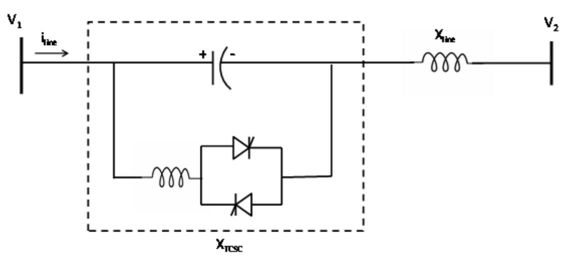

Figure 5: Transmission line with a TCSC

The effective line reactance with the TCSC in capacitive mode is given by the expression:

$$X_{eff} = j(X_{line} - X_{TCSC})$$

Active power transferred is given by the expression:

$$P_T = -\frac{V_1 V_2}{X_{eff}} Sin(\delta_{12})$$

The decrease in line reactance causes an increase in power transferred on the line; this improves synchronising power.

3.1. Illustrate TCSC action

In order to demonstrate practical application of a TCSC, a simple network is shown in Figure 6 and comprises a generator supplying an infinite bus via two connected transmission lines, with one of the transmission line series compensated using a TCSC.

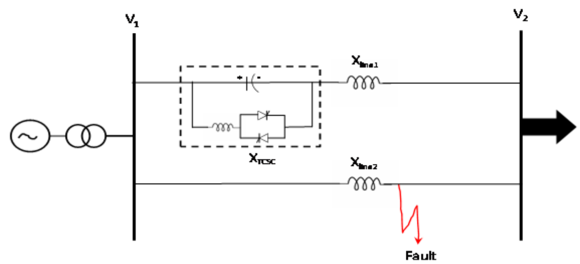

Figure 6: Network to illustrate TCSC action

The TCSC action is illustrated by a three phase fault simulated on a line without a TCSC and the fault is cleared by tripping the faulted line. The TCSC would be triggered to regulate levels of compensation of the remaining line, so as to improve its power transfer capability and improve stability of the generator. Figure 7 depicts the impact of TCSC action on transient stability margin. [6]

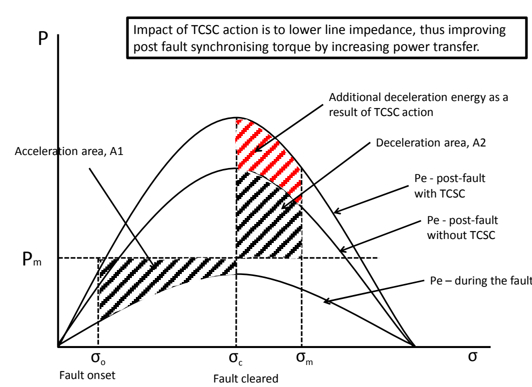

Figure 7: Impact of TCSC action on rotor stability

Post-fault, with an uncompensated line remaining, power transfer is substantially reduced due to overall line reactance increase.

When a TCSC is applied, the reduced line impedance yields increased transfer over the remaining line, increases electrical torque and allows the generator to decelerate faster (illustrated by the increased deceleration area in red).

4. Simulation on the SA National Grid: CFCT Studies

The first part of the analysis was to determine the CFCTs for three-phase line faults conducted without the TCSC. The lowest fault clearing time is considered the critical fault clearing time (CFCT) for Medupi generators.

Subsequently, studies were conducted to determine the new CFCTs when the TCSC is applied on the lines, one at a time. The line that yields the most benefit from TCSC application is selected. Compensation level is varied to demonstrate the impact on stability margins.

4.1. CFCTs without TCSC

To simplify this exercise, only three phase line faults were simulated on transmission lines connected to Medupi PS. Matimba PS and connecting lines were not included. Figure 8 depicts the network under study, comprising Matimba (6 x 664 MW) and Medupi (6 x 846 MW) power stations. The lines connected to Medupi range from about 200 – 300 km.

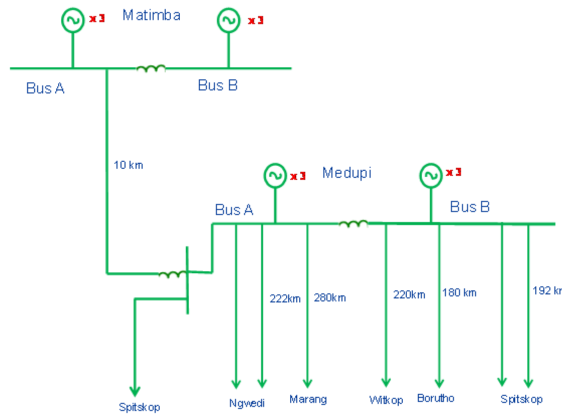

Figure 8 : Network under study [1]

The simulation was run for 1s and three phase line faults were then applied and the fault was cleared by tripping the faulted line. The fault duration was varied until the critical fault clearing time was determined. Table 1 is a summary of calculated CFCTs without applying the TCSC.

Table 1 : CFCTs without TCSC application

Faulted line	CFCT (ms)
Medupi – Witkop 400 kV line	85
Medupi – Marang 400 kV line	90
Medupi – Spitskop 400 kV line	87
Medupi – Borutho 400 kV line	84
Medupi – Ngwedi 400 kV line	88

As shown in Table 1, the three phase line faults are most onerous on Medupi – Borutho and Medupi – Witkop 400 kV lines. For the purpose of simulating CFCTs when the TCSC is applied, and for simplicity, the Medupi – Borutho line was used as a reference, such that the intervention yielding the best improvement of CFCT on this reference line would be taken as preferred solution.

5. Impact of TCSC on stability margins

5.1. Modelling of TCSC in PSS/E

The TCSC model as applied in PSS®E analysis software was used. PSS®E uses the CRANIT model to simulate the TCSC action. Figure 9 depicts the CRANIT model control function [7].

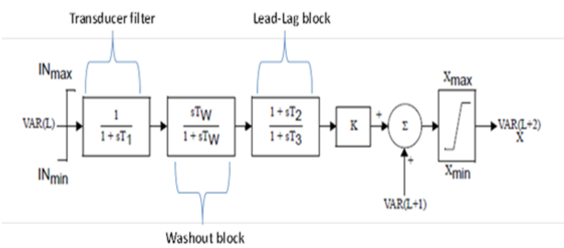

Figure 9: Block diagram control function of TCSC model

The model consists of constants, variables and internal constant inputs that the user can specify.

The **constants** include the following:

- IN_{max} and IN_{min}, which are maximum and minimum (pu) input signals/limits, respectively.
- K is the gain
- X_{max} and X_{min}, which are (pu) maximum and minimum output (line reactances), respectively.

The **time constants** include the following: T_1, T_w and T_2, T_3 are time constants for the transducer filter, washout block and lead-lag block, respectively. The lag block acts as a transducer filter and the lead-lag block ($T_1 > T_2$) compensates for the phase lag between input and the output signals.

The washout block serves as a high pass filter with time constant, T_w, sufficiently large to allow signals associated with the fault conditions (high frequency signals) to pass through.

The **variables** include VAR(L), input variable, VAR(L+1), initial output and VAR(L+2), which is the desired reactance. Switching of the TCSC could be made based on input variables such as branch power, branch current, or bus voltage, etc. The **internal inputs** to the model, which the user can specify include the following:

CRANIT Input Code - VAR(L):

- pu current on branch (branch between two busbars)
- pu power on branch (branch between two busbars)
- pu frequency difference between two busbars
- pu busbar voltage
- pu frequency deviation on busbar
- machine speed deviation (machine at busbar)

In PSS®E, the line (branch) impedance is adjusted by thyristor control of a reactor in parallel with a series capacitor.

The range of compensation limits, X_{max} and X_{min}, should include the original line reactance [7]. Upon initialization, model output VAR (L+1) and VAR (L+2) are set equal to the power flow line reactance. As the simulation progresses, the effective branch reactance is modified in response to changes in controller input VAR (L).

5.2. Selecting the line for compensation

The fault on the Medupi-Marang line has the highest CFCT; therefore this line was selected for TCSC application, so as to improve the CFCTs for the other lines.

5.3. Impact of varying the degree of series compensation

The compensation level on Medupi – Marang line was varied from 10% to 80%. A three phase line fault was simulated on the Medupi – Borutho 400 line at each level to determine the CFCT.

Figure 10 depicts the results. The CFCT ranges from 85 ms to 93 ms, at 10% and 80 % compensation levels, respectively.

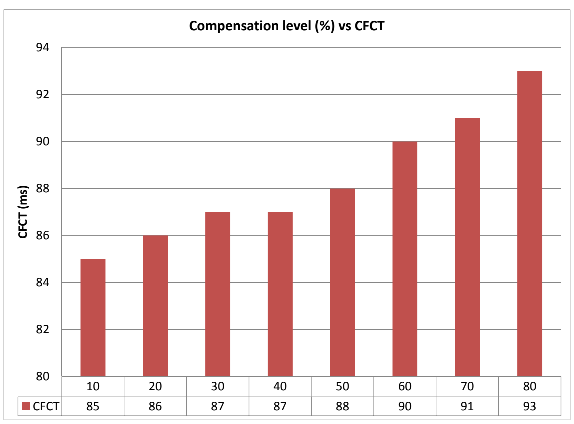

Figure 10: Impact of series compensation level

5.4. Impact of additional lines

The impact of adding lines on corridors was simulated. A new line was added separately in parallel with each connected to Medupi and a three phase line fault was simulated on the Medupi – Borutho 400 kV line to determine the improvement in transient stability margin.

Table 2 gives a summary of the calculated CFCTs. The addition of a second Medupi – Borutho line results in the largest improvement in CFCTs on Med-Borutho line (reference line). As shown in Figure 10, a compensation level of 70 % yields a similar margin (CFCT: 91 ms), comparable to adding a second Medupi – Borutho line.

Table 2 : Impact of addition new lines on CFCT

<table>
<tr><th>Additional lines</th><th>CFCT on Med-Bor without TCSC (ms)</th><th>CFCTs (ms)</th></tr>
<tr><td>2nd Medupi – Witkop 400 kV line</td><td rowspan="5">84</td><td>90</td></tr>
<tr><td>2nd Medupi – Marang 400 kV line</td><td>87</td></tr>
<tr><td>3rd Medupi – Spitskop 400 kV line</td><td>88</td></tr>
<tr><td>3rd Medupi – Ngwedi 400 kV line</td><td>87</td></tr>
<tr><td>2nd Medupi – Borutho 400 kV line</td><td>91</td></tr>
</table>

Increase of the CFCT from 84 ms (without TCSC) to 91 ms (7ms) would enable connection of additional generation in the region of 600 MW.

5.5. Practical sizing of TCSC and physical interaction with system

Size consideration: Simulations in this section were done at 70 % compensation level on the selected line. For cost effectiveness and to reduce steady state losses, compensation is normally split between the fixed and variable. [8] This case assumes 50 % fixed and 20 % variable (TCSC).

Calculation of series capacitive reactance with fixed 50% fixed compensation is given below.

Effective series reactance, X_{eff} = j (X_L - X_C) where, X_L is the line inductive reactance and X_C is the series capacitor reactance. The Medupi – Marang line reactance, X_L is 0.04165 pu. Therefore at 50% compensation level, X_{eff} = X_C = 0.0208 pu.

In blocked mode of operation, a dynamic compensation level of 20% corresponds to X_C of 0.0125 pu.

Using the formula below the required reactor size, X_{TCR} can be determined.

$$X_{TCSC}(\alpha) = \frac{X_C X_{TCR}(\alpha)}{X_{TCR}(\alpha) - X_C}$$

The reactor size will depend on the SSR mitigation needs. SSR studies were excluded from this analysis.

Physical mechanics of interaction

Figure 11 shows rotor angle change in study area generators when the line fault is applied.

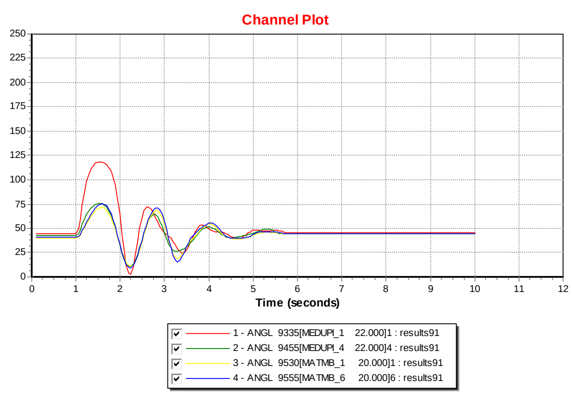

Figure 11: Generator rotor angles at Medupi

The generator unit closest to the fault experiences the largest rotor angle change. Less impact is experienced by nearby generator units due to 400 kV busbar series reactors at Medupi and Matimba.

Figure 12 shows the Medupi – Marang line reactance being altered from the fault onset by TCSC action. Reduction of line impedance increases power transfer thus improving transient stability margins.

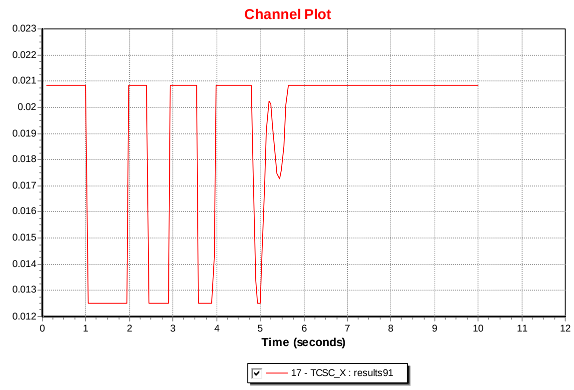

Figure 12 : Medupi-Marang line reactance (TCSC output)

5.6. Comparison of alternatives

The options were compared based on environmental impact, technical and financial merits.

Table **3** highlights the advantages of TCSC application over addition of new lines.

Table 3 : Alternatives comparison

Description	2nd Medupi – Borutho 400 kV line (180 km)	TCSC on Medupi Marang line
Environmental impact	assessment over two years	within a year
Servitude acqusition	over 3-5 years	within a year
Technical feasibility	established alternative	new in most developing countries
Capital cost	costly	cost effective solution
Building period	approximately 2 years	Within a year

6. Conclusions

This study demonstrates that use of TCSCs is a technically viable, cost-effective alternative and results in less impact on the environment compared to a traditional solution of building additional lines. TCSC application can enable additional generation connection in areas limited by transient instability.

Power System Engineers should consider TCSCs as viable alternatives where power transfer and stability limits exist, coupled with funding and environmental constraints; TCSC has the advantage of enabling capacitive compensation near thermal generators, due to its ability to eliminate SSR risks when tuned adequately.

7. References

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