TCSC as a Transient Voltage Stabilizing Controller

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Abstract: TCSC has been proposed to enhance the voltage stability by changing the reactive power distribution in the power system. Authors have discussed the effect of TCSC on steady state voltage stability and small-signal voltage stability. This paper discusses the TCSC's enhancement on transient voltage stability. A TCSC model that is suitable for transient voltage stability analysis is proposed. This model is tested on a multi-machine system including all the key elements relevant to system voltage performance. The simulation shows that angle-stability-enhancement-like TCSC controllers offer little help for certain transient voltage stability crises. Based on this analysis, a new TCSC controller is proposed and proved to enhance the transient voltage stability.

Keywords: voltage stability, transient, FACT, TCSC, control, model, stability enhancement

I. INTRODUCTION

Improvement of voltage and current limits on the power electronics devices leads to a fast development of Flexible AC Transmission Systems (FACTS) in the last decade. Thyristor controlled series capacitors (TCSC) have been widely studied by many researchers. Several TCSC devices also have been installed and operated by some utilities [1,2].

The primary uses of TCSC are to enhance the power system angle stability and to mitigate the sub-synchronous resonance by regulating real power and maximizing transient synchronizing torque between the interconnected power systems [3,4]. However, the inserted series capacitor also affects the reactive power distribution in the interconnected power systems. Thus, Paper [5] suggests that TCSC be used to enhance the voltage stability.

A recent paper investigates the effect of the TCSC on the voltage stability with a detailed steady state model [6]. The authors model the voltage stability as an optimization problem to maximize the loadability margin with respect to system parameters, such as impedance of transmission lines. The result shows that TCSC can greatly improve the system loadability margin using the optimal TCSC setting. In the paper, the transient process is assumed to settle down very fast, thus TCSC's effect on transient voltage stability could be ignored. However, there is a concern that the dynamic process may affect the voltage stability greatly. Especially when dynamic load is connected in the system, the interaction between the dynamic load and TCSC cannot be ignored.

Paper [7] discusses the effect of TCSC on the small signal voltage stability for a simple power system with an infinitive bus and a dynamic load. The small signal voltage stability region is derived for this simple system. The paper has one serious drawback that infinitive bus is not a good model for a generator for voltage stability studies since only the voltage instability caused by insufficient transfer capability can be examined. It is well known that the generator field current limiting action limits the output of the reactive power, which is essential in the voltage stability analysis.

In this paper, a TCSC transient voltage stabilizing controller is proposed. In a transient voltage stability analysis, TCSC is operated in a big range for a long period, which is very different from small signal voltage stability. Thus the operation limits of a TCSC must be considered. In section II, a TCSC dynamic model for the transient voltage stability analysis, which includes TCSC load management, is derived. Because TCSC device is intended to be used in a close loop manner, the effect of close-loop TCSC controller is also considered in this new model. Section III describes a modified WSCC 3-machine system, which is used to test our new model. Critical elements relevant to system voltage performance are included in the test system. These elements include induction motors, on-load tap-changer transformers, automatic voltage regulators and overexcitation limiters for generators. The system models and its solution method are also discussed in this section. The transient voltage stability control with TCSC is simulated in section IV. The simulation shows that the angle-stability-enhancement-like TCSC controller can not resolve some transient voltage stability crises. Then a novel controller to enhance the transient voltage stability is proposed and simulated to demonstrate its effectiveness. We conclude the paper at the last section.

II. A NEW TCSC MODEL

There are many papers on its steady state models [9, 10] and dynamic models [11, 12]. Paper [9] develops a general power flow model for TCSC, which provides a detailed relationship between the effective fundamental frequency impedance and the firing angle. Paper [10] proposes another steady state model. Because the "stored charge effects" of capacitor in the

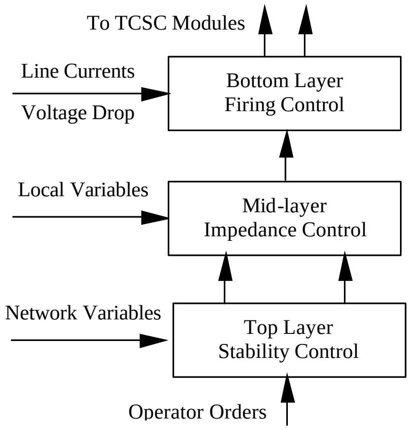


Figure 1 A Layered Control Structure of TCSC

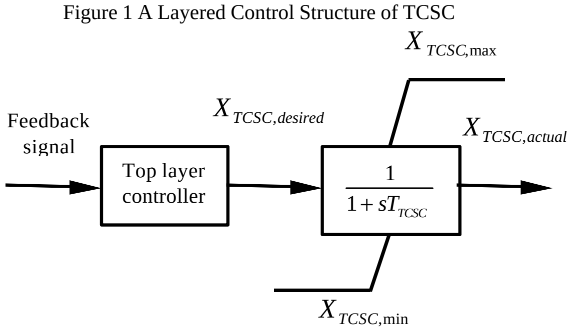


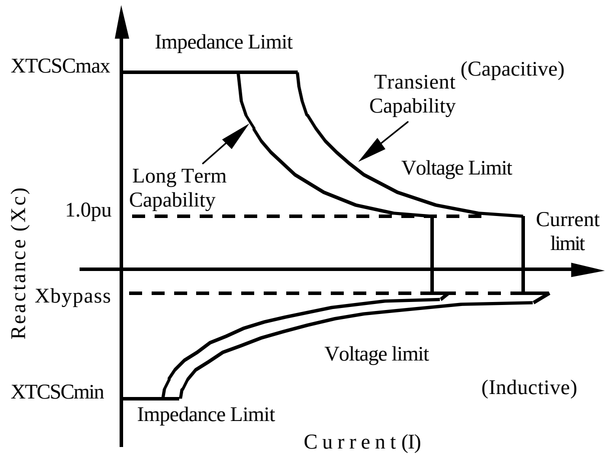
Figure 2 TCSC model for transient voltage stability analysis

TCSC device are considered, this model is more accurate for long operation periods. Paper [11] develops a linear dynamic model for a simple power system with TCSC in the rotor reference frame. This model is valid for small perturbations near a steady-state operating point. Examples also show that the linear gains vary greatly over a range of firing angles, which demonstrates the nonlinear behavior of a TCSC.

For a closed loop TCSC, Fig. 1 is a typical hierarchical structure [13]. The bottom layer generates the trip signal and the middle layer controls the impedance of TCSC device. The time ranges of both bottom layer and mid-layer are much less than the time range of transient voltage stability analysis. Thus the dynamics caused by lower two layers can be approximated by a single first-order lag. With this simplicity, the TCSC model is represented in fig. 2.

The first block is the control function for top layer control. It is from the feedback signal to the desired impedance. The orders from operators are treated as reference signals, thus are part of control function and are not explicitly expressed. The typical feedback signals are local power flow, local current or local frequency or their combinations. Two examples of control functions are discussed in section IV.

The second block is from the desired impedance to the TCSC's actual impedance. The time constant is the sum of the natural response of the TCSC, firing control and impedance control. With this approach, details from the firing angle to the effective fundamental frequency impedance are hidden. The severe nonlinearity due to change of firing angle



(a) Transient and long-term TCSC overload capability (adopted from Figure 6 of [12])

If (V,I) is out of transient overload capability curve

$$X_{TCSC,\max} = X_{TCSC,\min} = X_{bypass}$$

Else if (V,I) is out of long-term transient overload capability curve for more than 10 second

$$X_{TCSC,\max} = X_{TCSC,\min} = X_{bypass}$$

Else

$X_{TCSC,\max}$ *and* $X_{TCSC,\min}$ *are determined by long-term transient overload capability from line current*

(b) Control logic for load management

Figure 3 Load Management of TCSC

is also concealed. A diagram similar to the second block is also provided in paper [12].

$X_{TCSC,\max}$ and $X_{TCSC,\min}$ are allowed impedance range for a TCSC device. When actual impedance is out of this range, TCSC goes to a bypass mode. A small inductance is inserted in the line to force the current down. This is supervised by a load management function.

Fig. 3a illustrates a typical overload capability of a multi-module TCSC device. The outer curve is the transient overload capability, which is good up to 10 second, and the inner curve is the bng-term overload capability, which is good up to 30 minutes. The continuous operation capability is out of the range of the transient voltage stability studies; thus, it is not presented in the figure. For the given current, these curves provide the maximum and minimum impedance limits. Fig. 3b is the control logic of load management function. The inputs to this function are voltage drop that crosses the TCSC (*V*) and line current (*I*).

III. A Test System

The modified WSCC 3-machine system is used as our test system. A TCSC is installed at the middle point of line 6-9 to enhance the stability. The system configuration is shown in fig. 5. Load flow data, machine and exciter data can be found in reference [14]. To simulate the transient voltage stability,

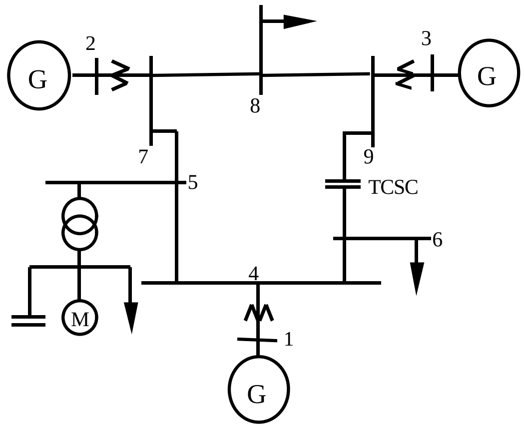


Figure 4 WSCC 3-machine system

key elements relevant to system voltage performance are included in the test system. They are

- dynamic load, which includes on-load tap-changer (OLTC) transformer and induction motor, and
- excitation system, which includes automatic voltage regulator and overexcitation limiter.

3.1 Dynamic Load

The first key element is the dynamic load. There are three loads in WSCC system at bus 5, 6 and 8. To keep it simple, only load at bus 5 is modeled as a dynamic load. At the other two buses, constant impedance load are used.

At bus 5, local distribution system is connected to the transmission system by an OLTC transformer. The local distribution system is assumed to have both residential load and industrial load and is congregated as the combination of aggregated induction motor, compensation static capacitor and constant impedance load.

The induction motor is a weighted aggregate of residential and industrial motor, which is a type 6 of IEEE recommended typical induction motor [15]. Because it is an aggregated induction motor, there is little benefit to use high order model. Fig. 5 is the equivalent electrical model of induction model used in the paper. Motor's dynamics is modeled as

$$2H_0 \frac{ds}{dt} = T_L(s)w_0 - P_e$$

Where P_e is the real power consumed by a resistance R_r/s .

The power factor of this motor is 0.6, which is too low for a distribution system to tolerate. A compensation static capacitor is paralleled with this induction motor. The power

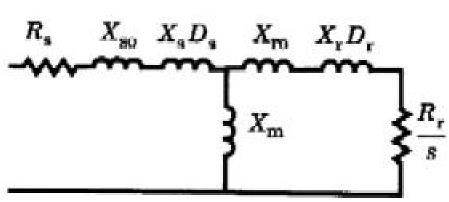


Figure 5 Equivalent electrical model of the induction motor

factor of the combined induction motor and capacitor is 0.9, which is reasonable for a load access point for a distribution network. This induction motor absorbs 35% real power input at bus 5. Other real power is consumed by constant impedance load, which is paralleled with the induction motor.

Models of OLTC transformers are given by IEEE task force [15]. A transformer will delay 40 second after it senses the over-voltage/under-voltage to avoid excessive operation. After that, there is a 4-s-delay between two adjacent taps. At this time, the discrete model is

$$a(k+1) = a(k) + df\left(V(k) - V^{ref}\right)$$

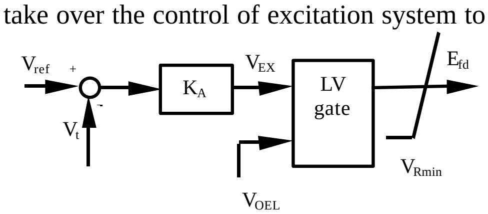
where

$$f\left(V(k) - V^{ref}\right) = \begin{cases} 1 & V(k) - V^{ref} > \Delta V \\ 0 & \left|V(k) - V^{ref}\right| < \Delta V \\ -1 & V(k) - V^{ref} < -\Delta V \end{cases} .$$

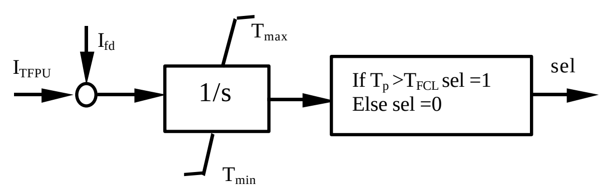
3.2 Excitation System

Automatic voltage regulators and overexcitation limiters for generator are other key components to be considered.

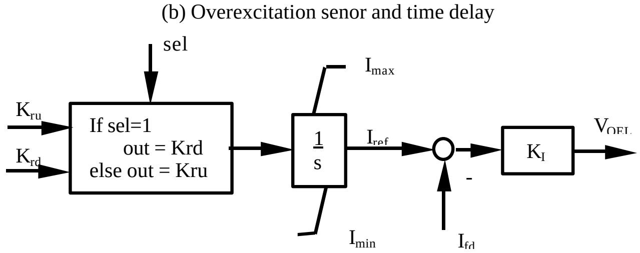
- Automatic voltage regulator maintains the terminal voltage as constant as it can by increasing the excitation voltage and/or field current for rising reactive power demand.
- Over excitation limiter prevents the field winding from overheating by a prolonged field over-current. After detecting the high field current condition, a new control signal is generated after a time delay. This signal will be added to the control signal of automatic voltage regulator or take over the control of excitation system to decrease



(a) Simplified exciter and take-over control



(b) Overexcitation senor and time delay



(c) Reference signal reduction and over excitation signal generation

Figure 6 Simplified AVR and OEL

the exciter's terminal voltage. This device limits the reactive power a generator can provide.

Fig. 6 provides the structures of simplified AVRs and OELs. These two devices are installed at all three machines. The abbreviations used in the figure are the same as IEEE recommended models [16].

In the above structure, OEL will take over the excitation control when OEL control signal is less than excitation control signal (fig. 6a). Figure 6b are detected signals that are used to activate the time delay. In fig. 6c, K_{ru} is a positive slope and K_{rd} is a negative slope, which dictates how reference signal of OEL is changed. When there is an overload signal trigged by fig. 7b, the reference signal is reduced with the speed of K_{rd}. When the overload is cleared, the reference signal is increased with the speed of K_{ru}. The reference signal is limited by $I_{\max}$ and $I_{\min}$.

3.3 Events

- At $t = t_0$ = 0s, there is a fault at the line 5-7 near bus 7. Bus 7 is treated as solid grounded.
- At $t = t_1$ = 0.16s, the faulted line is isolated with breakers.
- At $t = t_2$ = 6s, the fault is cleared and the line is back to service.
- After $t = t_3$ = 15s, there is a load change at bus 5 with time. To keep it simple, it is assumed that equivalent impedance changes as
$$Z(t) = Z(t_3) + k_P(t - t_3).$$

The first three events are used to simulated fault related transient voltage stability. The last event emulates the system level load changes, which may cause load-build-up related transient voltage instability.

3.4 System Model

Transmission system models and machine models are similar to that for angle stability analysis, which is thoroughly discussed in reference [14]. Together with models discussed in section 3.1 and 3.2, the whole system model can describe in the form of

$$\begin{aligned} \dot{x} &= f(x, y, z(k), t) \qquad t(k) \le t < t(k+1) \\ 0 &= g(x, y, z(k), t) \qquad t(k) \le t < t(k+1) \\ z(k+1) &= h(x, y, z(k), t) \qquad t = t(k) \end{aligned}$$

In the above model, x denotes continuous dynamic state variables of the system, such as machine angels; y is quasi-steady state variables such as voltages in the transmission system; z is used to depict discrete events, such as operation of OLTC transformer and the topology change of transmission network.

The sequence method is used to solve system. First, the differential equation and difference equation are solved by modified Euler method. Then modified Gauss-Siedel method is used to solve the quasi-steady state equation. Different from standard load flow, angles and magnitudes of the internal voltages of all machines, which are part of continuous dynamic state variables, have been determined by the differential equations at the first step.

IV. TCSC CONTROLLER

In the last several years, many studies on TCSC control schemes have been reported. Most of them focused on power system angle stability enhancement and sub-synchronous resonance mitigation. For the practical reasons, such as availability of the measurement and the burden of calculation, relatively simple controllers are used in the installed TCSC devices [17].

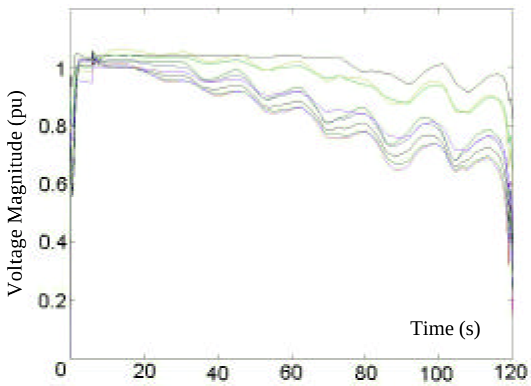
This practical angle-stability-enhancement-like controller is used directly to check its ability on transient voltage stability.

- At $t = t_1$, when the relay system send signal to breakers to trip the line, this signal is also send to TCSC. The maximum capacitor is inserted into the transmission line. TCSC is inserted to the system with maximum capacitor.
- At $t = t_2$, when the line returns to the service, TCSC is in damping control mode. In the damping control mode, the magnitude of current at line 6-9 is used as the feedback signal. Ignoring the small time constant in the measurement link and lead-lag link, transfer function of damping control can be expressed as
$$X_{TCSC,desired} = \frac{k_{TCSC}\, s}{1 + sT_{TCSC}} \left| I_{line} \right|$$
where $\left| I_{line} \right|$ is the magnitude of current at line 6-9.

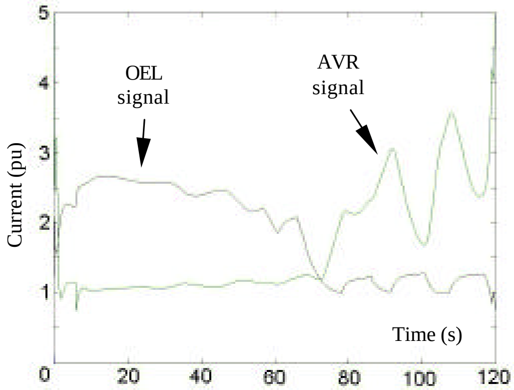
Fig. 7 is the simulation result with this controller. Fig. 7a is a profile of all bus voltages and machine internal voltages. This TCSC controller handles the first three events successfully. However, after the fourth event happens, system voltages begin to drop. At $t = 70s$, the lowest voltage is around 0.7 pu. System collapses at $t = 120s$.

Fig. 7b shows control signals generated by automatic voltage regulator and over excitation limiter for machine 1. Before $t = 70s$, AVR signal is less than OEL signal. Thus it is taken as excitation system signal. After this instance, OEL signal is taken as excitation system signal. This instance coincides with the time when voltage profile has a big drop. The switch instances of other two machines are less than that of machine 1. This suggests that there is not enough reactive power in the system after all OELs take over the control of excitation systems.

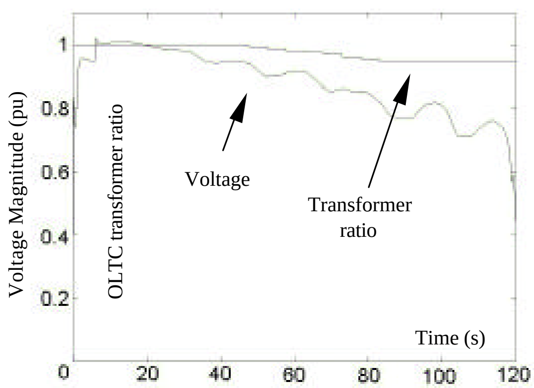
Figure 7c shows the terminal voltage at the distribution system and ratio of transformer. The tap-changer is activated after OLTC transformer senses the low voltage at the



(a) Voltage profile

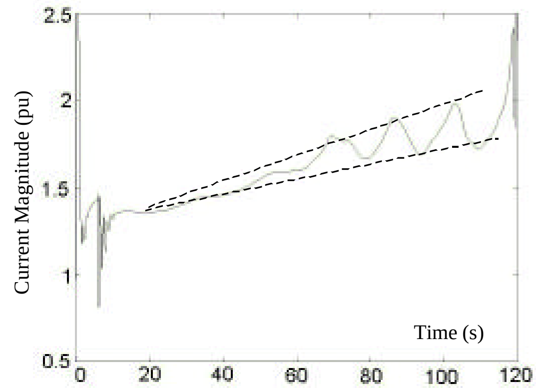


(b) Compression of AVR and OEL signals for machine 1

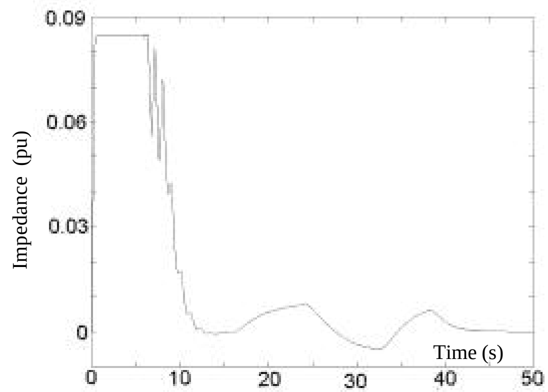


(c) Voltage at distribution system and transformer ratio

Figure 7 Simulation Result with angle-stability-enhancement-like TCSC controller



(a) Magnitude of current at line 6-9



(b) Desired TCSC impedance (Capacitive)

Figure 8 Input and output of angle-stability-enhancement-like TCSC controller

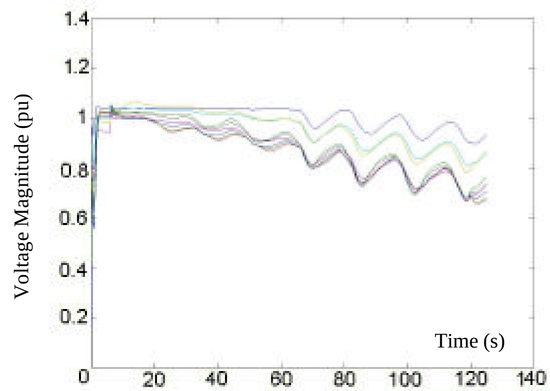


Figure 9 Voltage profile with new TCSC controller

terminal of distribution system for 40 second. After the first tap moves, taps keep on moving until the lowest tap limit is hit. This operation of OLTC is based on this idea.

Reduced ratio decreases the equivalent impedance at the primary side. If the primary side has enough reactive power, more reactive power goes through OLTC transformer, thus voltage at the second side is increased.

However, there is not sufficient reactive power in the system. Thus, OLTC transformer is useless to support the voltage at the distribution system for this situation.

In this control scheme, TCSC impedance is controlled, not by the line current magnitude, but by the change of the line current magnitude. For the current magnitude like fig. 8a, whose average is approximated as

$$|I_{line}| \approx k_{line}(t-T)+I_T \ ,$$

after the fourth event, output of TCSC controller is approximated as

$$X_{TCSC,desired} \approx k_{TCSC}k_{line}$$

The inserted series capacitor is unchanged even with the build-up of system load. Thus the reactive power distribution is unaffected by the TCSC. This can be used to explain why angle-stability-enhancement-like TCSC controller does not improve load-build-up related transient voltage stability for a crisis like event 4.

Based on above analysis, TCSC control must have the ability to sense the system load change. There are several methods can provide this information. From fig. 8a, local current is a good indicator for the system load level. The new TCSC control scheme is

$$X_{TCSC} = \frac{k_{TCSC} s}{1 + sT_{TCSC}} |I_{line}| + k_{TCSC2} g(|I_{line}| - I_0)$$

where

$$g(x) = \begin{cases} x & x > 0 \\ 0 & x \le 0 \end{cases}.$$

The first term is still used to enhance the damping of the system and handle first three events. The second term is used to adapt the load level change. I_0 is a pre-selected load level, which is pre-fault line current magnitude in the simulation. Fig. 9 provides system voltage profile. Comparing it with fig. 7a, we can observe the improvement of our new TCSC controller.

V. CONCLUSION

This paper addresses the transient voltage stability controllers. There are three contributions in this paper.

1. In this paper, a TCSC model, which is suitable for transient voltage stability control, is proposed. This model includes TCSC's close-loop controller and load management function.
2. This model is tested with a multi-machine system. Four key voltage performance related elements, induction motor, OLTC transformer, automatic voltage regulator and over excitation limiter are included.
3. The simulation shows that angle-stability-enhancement-like TCSC controller can enhance transient voltage stability caused by faults. However, more information is needed to handle transient voltage stability caused by system load change. A new TCSC controller is proposed to enhance both fault related and load build-up related transient voltage stability. This ability is verified by the simulation.

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BIOGRAPHY

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