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Comprehensive review of gate-controlled series capacitor and applications in electrical systems

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Abstract: Flexible AC transmission system series compensation, such as series switched capacitors including gate-controlled series capacitor (GCSC) plays an important role to enhance grid system transfer power, stability, power quality and loss reduction. GCSC devices are implemented using fixed or switched capacitor in parallel with a pair of anti-parallel gate-commuted switches. They are connected in series of transmission and distribution lines and are commonly used to control the power flow on congested transmission lines. This study presents a review of GCSC devices and future perspectives.

1 Introduction

In the last three decades, the increasing prices of conventional fossil fuels and changes in global warming and environmental pollution have led to increased interest in electric power generation from renewable energy sources (RESs) [1–3]. However, the widespread use of RESs as distributed generation (DG) systems, together with the increasing electric power demand, challenges the traditional electrical network structure, which requires greater emphasis on electric system operation and control [4–7]. This is why there is a growing need for standardisation and performance criteria to measure the power quality [8–10]. In addition, the increase in demand of RESs in distribution systems has changed the power quality phenomena in modern electrical grids [11], as shown in Fig. 1.

Flexible AC transmission system (FACTS) technology can contribute to more efficient energy utilisation, demand control, voltage stabilisation, power quality enhancement, power factor correction and harmonic mitigation. They are of special interest for long transmission lines used to connect, for instance, remote generation plants to large urban areas [12–17]. The basic concept of FACTS devices is based on the use of high voltage power electronics to control real and reactive power flow and also voltages in the transmission system [12–14].

FACTS controllers, in addition to improve the steady-state condition, can also help during transients, and hence contribute to the improvement of the grid power quality. FACTS devices can be used to feed more consumers instead of upgrading or building new transmission lines, substations or even power plants in electrical networks [15, 16]. FACTS devices play an important role in

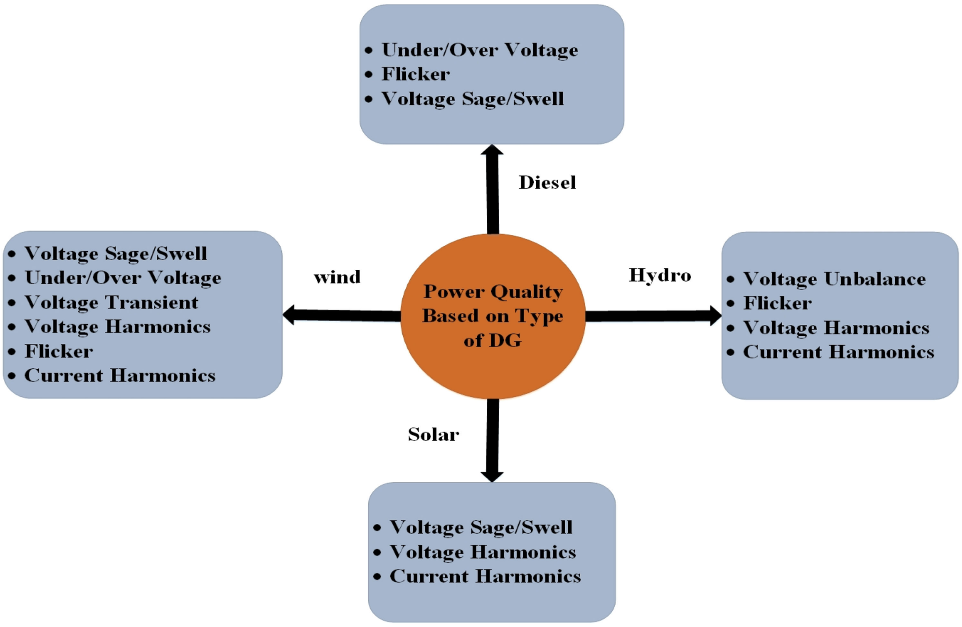


Fig. 1 *Power quality problems from DG sources*

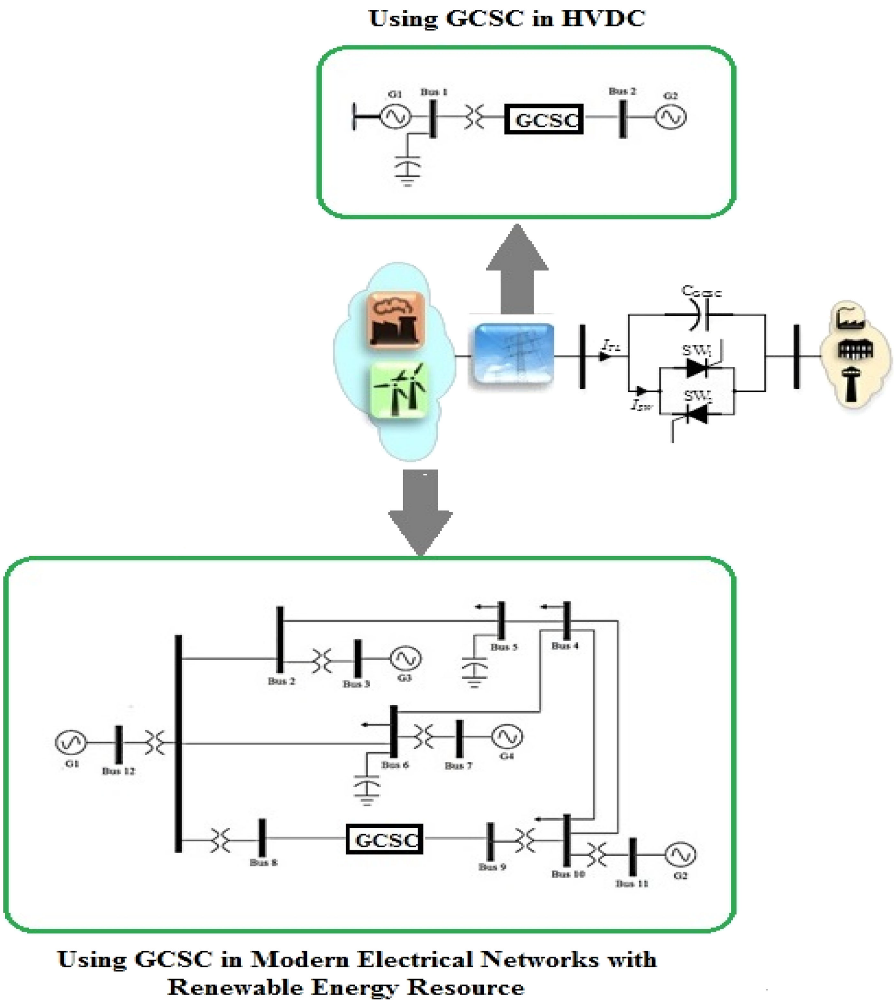


Fig. 2 *GCSC configuration and installation in a transmission line and application in HVDC and modern electrical networks*

traditional/modern electrical networks by helping the adjustment of power flows and securing loading of the transmission lines. Moreover, in modern networks, they improve power quality using RESs and can help to handle modern loads better, such as electrical vehicles. For these reasons FACTS devices and smart control strategies have been gaining a more prominent role in the generation from RESs such as solar, wind and sea waves [17–20].

Among the FACTS devices, the series compensation is an economic method of improving power system stability of the electricity lines, increase power transmission capability, reduce system losses, improve the voltage profile of the lines and optimise the power flow between parallel lines [21–26]. The main reasons to use gate-controlled series capacitor (GCSC) as new controlled series compensators are to enhance power transfer capacity and improve transient stability by mitigating sub-synchronous resonance (SSR) and damping power oscillations [27–29]. However, the use of GCSC adds up to the cost and complexity of the grid control/operations.

Thyristor controlled series compensation (TCSC) was introduced as the first generation of FACTS series compensation [30]. A TCSC consists of one capacitor connected in series with the line with two thyristors connected in parallel to the capacitor. The TCSC is a kind of static voltage controller but with a simpler structure [31].

Although TCSC is suitable equipment to increase transmission capacities and improve overall power network's stability, TCSC requires the use of other equipment due to:

- The non-linear effects on system stability,
- discontinuous impedance, and
- harmonic injection.

GCSC is a one of the series FACTS controllers that was introduced recently. The GCSC consists of a capacitor and a pair of gate turn-off (GTO) thyristors connected in anti-parallel [29, 32]. Among the FACT devices, the GCSC is a best choice to control the risk of SSR in traditional power systems [33, 34]. This paper is a comprehensive review of GCSC devices. The main contributions of the paper are:

- a comprehensive review of GCSC devices, operation and applications,
- power oscillation damping studies,
- comparison, advantages and disadvantages of GCSC with other series FACTS devices, and
- a review of future challenges of GCSCs.

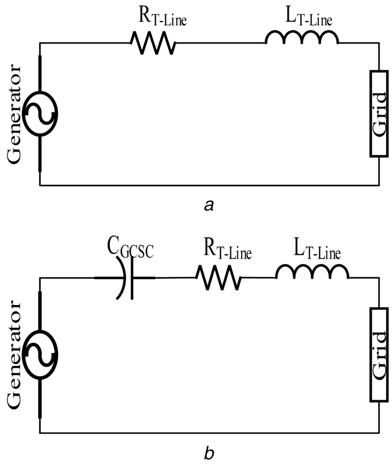
The paper is organised as follows. Section 2 reviews the GCSC operation. SSR, power oscillations, damping and applications in power systems are introduced in Section 3. Future research and challenges with GCSC is presented in Section 4. Finally, the main conclusions are summarised in Section 5.

2 Equations and operation

2.1 Circuit topology and operation modes

The first configuration for a series capacitor modulated by anti-parallel GTO thyristors was proposed by Karady *et al.* [35]. Then, Watanabe *et al.* [33] suggested that any other high current rating switches, such as integrated gate commutated thyristor, can be utilised for the modulation of the series compensation capacitor (Fig. 2).

The series capacitor is used in long transmission lines in order to compensate the line reactance, decrease voltage drop and control the line flow. However, a constant capacitor arises practical



a

b

Fig. 3 *Equivalent circuit of the system*
(a) On-state switch; and ***(b)*** Off-state switch

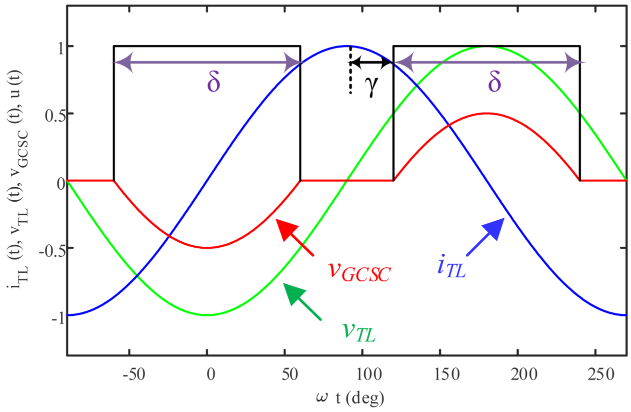


Fig. 4 *Switching pulse, transmission line current (i_{TL}), and voltage waveform (v_{GCSC}) of a GCSC*

problems such as SSR. This encouraged the researchers to replace constant capacitors with GCSC, as a countermeasure against SSR. Fig. 3 shows the operation modes of the GCSC.

By controlling the firing angle of the switches, a variety of compensation levels are achieved. When the semiconductor switches are turned on, the capacitor is bypassed, and there is no line reactance compensation (Fig. 3*a*). The switches are turned on when the voltage across the capacitor is zero to avoid strong voltage and current transients, as shown in Fig. 4. On the contrary, when the semiconductor switches are turned off, the capacitor is in series with the transmission line reactance and behaves the same as a constant compensation capacitor (Fig. 3*b*). Turning off the semiconductors happens at a specific control angle γ represented in Fig. 4 [36], and it determines the level of line impedance compensation. Analysis done by Karady *et al.* [35] shows that the system does not experience voltage transients when turning off the switches.

2.2 Mathematical analysis

To obtain the equations that model the behaviour of the GCSC, it is considered that the line current is not affected by the compensator operation [37]. Therefore, the line current is considered a sinusoidal waveform as follows:

$$i(t) = \sqrt{2}I_0\sin(\omega t - \varphi) \tag{1}$$

According to Fig. 4, the gated controlled switches are off during an interval γ each half a cycle. During that interval the capacitor voltage is

$$\begin{aligned} v_{\rm C}(t) &= \frac{1}{C}\int_{\gamma}^{t} i(t)t\,{\rm d}t \\ &= -\frac{\sqrt{2}I_0}{\omega C}(\cos(\omega t - \varphi) - \cos(\omega\gamma - \varphi)), \quad \gamma \le t \le \pi - \gamma \end{aligned} \tag{2}$$

Equation (2) defines the capacitor voltage over the positive half a cycle. For the negative half a cycle, the capacitor voltage is negative and symmetric to the waveform described by (2). If the turn-off angle (γ) of the GCSC is equal to zero, the capacitor is conducting continuously like there is a constant compensation capacitor. On the other hand, when the turn-off angle is $\pi/2$, the capacitor is always bypassed and hence it is like there is no series compensator.

Accordingly, the voltage across the capacitor can be modulated by controlling the turn-off angle in the interval $[0, \pi/2\ ]$, resulting in a varying compensation level on the transmission line.

2.3 Harmonic distortion

As a result of the non-linear behaviour of the GCSC, it generates voltage harmonics that may exceed the standard levels. The voltage harmonics of the GCSC are [38]

$$\begin{aligned} V_{\rm Ch} &= \frac{4\sqrt{2}I_0}{\omega C\pi}\left\{\frac{\sin((h+1)\delta)}{2(h+1)} + \frac{\sin((h-1)\delta)}{2(h-1)} - \cos(\delta)\frac{\sin(h\delta)}{h}\right\}, \\ h &= 2n+1, \quad n = 1,\ 2,\ 3,\ \ldots \end{aligned} \tag{3}$$

where δ is equal to the half a cycle over which the capacitor voltage is not zero ($\delta = \pi - \gamma$). As the capacitor voltage has half-wave symmetry, no even harmonics appear in the voltage waveform, but only odd harmonics pollute the voltage.

Two configurations for GCSC have been proposed and analysed to decrease the level of harmonic distortion in GCSC voltage [38, 39]. The first method consists in using multi-module GCSC (MGCSC), which includes several (m) small scale GCSCs connected in series where their size is a portion ($1/m$) of the total compensation requirement. This approach controls the series GCSC modules sequentially [36], and thus it decreases the magnitude of the harmonics by a factor of m. However, it does not cancel any harmonic. In the second proposed solution, the GCSC is connected in series to the transmission line through a transformer. In this approach, the triplet harmonics are eliminated from the voltage waveform by the winding configuration of the transformer.

2.4 Effective impedance and control modes

The fundamental component of the GCSC voltage determines its effective capacitive impedance. The peak value of the fundamental voltage is

$$V_{{\rm C}_1}(\delta) = \frac{V_{\rm c0}}{\pi}(\delta - \sin(\delta)) \tag{4}$$

where $V_{\rm c0}$ is the peak value of the capacitor voltage and obtained as

$$V_{\rm c0} = \frac{\sqrt{2}I_0}{\omega C} \tag{5}$$

As a result, the effective capacitive impedance is defined by

$$X_{{\rm C}_1}(\delta) = \frac{X_{\rm c0}}{\pi}(\delta - \sin(\delta)) \tag{6}$$

The effective capacitance is controlled by manipulating the turn-off time of the semiconductors.

In practice, there are two approaches for GCSC operation, compensating voltage control by a closed-loop controller and compensation reactance control using an open-loop controller [36–40]. In the former mode, the GCSC maintains the compensating voltage ($V_{\rm C}$) constant while the line current varies between the

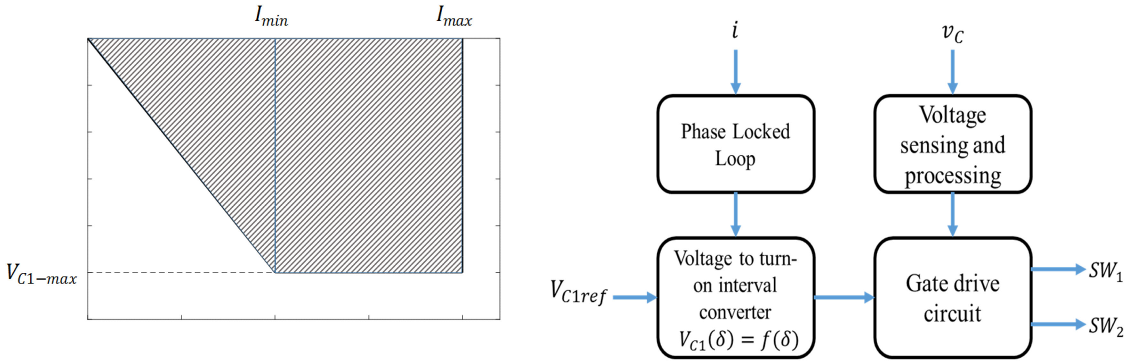


Fig. 5 *Compensation and block diagram of compensation voltage control mode*

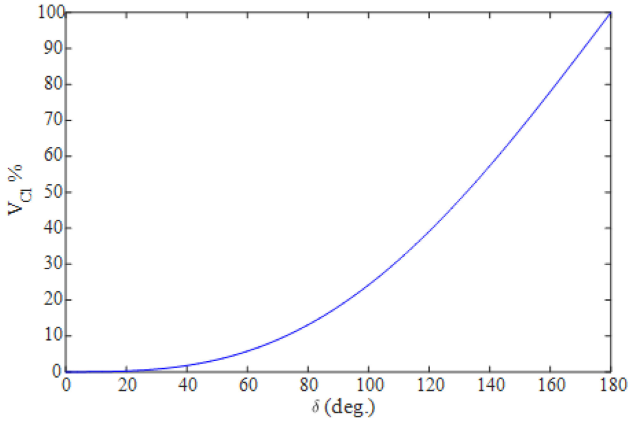


Fig. 6 *Fundamental component value of the GCSC voltage in terms of δ*

minimum and maximum values, indicated by $I_{\min}$ and $I_{\max}$, respectively, in Fig. 5.

To achieve this, the capacitive reactance (X_C) is selected in such a way that $V_C = X_C I_{\min}$, and when the current increases up to $I_{\max}$, the compensation voltage is kept constant by decreasing δ. Nevertheless, it increases significantly while δ goes from 60° to 180° [35] (Fig. 6).

In the compensation reactance control mode, the GCSC keeps the compensation reactance constant while the line current can change up to the maximum value (Fig. 7). This can be achieved by controlling the turn-off angle and consequently the capacitor voltage ($X_{C1}(\delta) = V_{C1}(\delta)/I(\omega t)$).

Moreover, there are two configurations for GCSC in terms of sequential voltage and current control principle of the series GCSC are discussed in Figs. 8*a* and *b*, respectively. If four modules of GCSCs together compensate maximum 40% of the series reactance of a transmission line, in case the 25% compensation is required, two modules would be totally inserted, one would be by-passed and the fourth compensates the remaining 5%.

2.5 Duality with thyristor controlled reactor (TCR) and compression with TCSC

One may realise the duality of the GCSC with the TCR [41]. Table 1 shows this duality by comparing voltage waveforms, connection to the grid, active and passive components, and control approaches [33].

It is worth mentioning that the sequential control of MGGCSCs to decrease the magnitude of harmonics of the capacitor voltage, is the dual of sequential control of parallel-connected TCRs to reduce harmonic magnitudes in the current waveform. By the same control strategy, the n TCRs, rated at $1/n$ of the total requirements, are controlled sequentially.

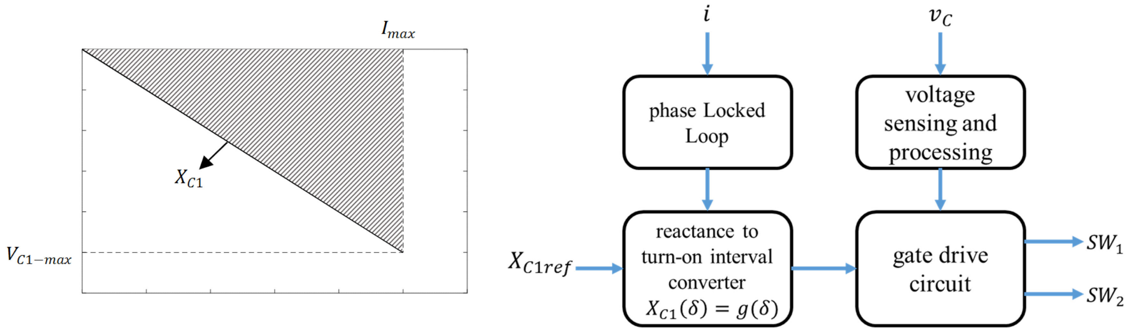


Fig. 7 *Compensation and block diagram reactance control mode characteristic*

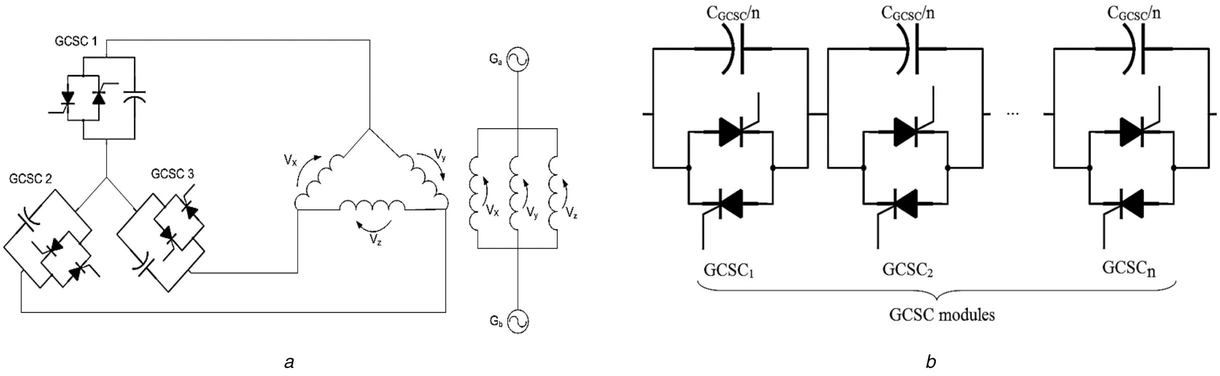


Fig. 8 *Sequential control principle of GCSC [38]*

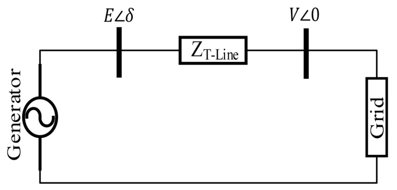


Fig. 9 *Equivalent circuit of a generator connected to an infinite bus by a transmission line*

Moreover, the comparison of GCSC and TSCS application is illustrated in Table 2.

3 SSR, power oscillations damping and applications of GCSC in power system

Large power generation units are usually connected to the grid through long transmission lines. The most important characteristic of these lines is high inductive reactance that consumes reactive power and results in voltage drops. The traditional approach to reduce the voltage drops on the long transmission lines is the use of a series capacitor, which injects reactive power into the system and compensates for inductive reactance. However, it was shown that the level of compensation is limited by the SSR [29, 42, 43]. This is due to the interaction between the electrical oscillation modes of the series compensated line and the mechanical oscillation modes of the generation unit, e.g. synchronous generators or wind farms [44]. Notwithstanding the fact that switched capacitors were first introduced to damp SSR, they improve the performance of the grid in terms of reactive power compensation, voltage stability, transient stability, power oscillation damping, and SSR damping as described in the following.

3.1 Reactive power compensation

As shown in Section 3, the GCSC introduces an equivalent capacitive reactance, X_{C1}, which is a function of the switching-off angle. This capacitive reactance decreases the transmission line impedance (XL) and increases the current flowing from the generation unit to the grid. Considering the simplified equivalent circuit of the transmission line with the GCSC, the current is

$$I = \frac{2V}{X_L - X_{C1}} \sin\left(\frac{\delta}{2}\right) \quad (7)$$

If $X_{C1} = kX_L$, where k is the level of compensation, then

$$I = \frac{2V}{(1-k)X_L} \sin\left(\frac{\delta}{2}\right) \quad (8)$$

As a result, the reactive power injected into the grid by the GCSC is

$$Q_{GCSC} = I^2 X_{C1} = \frac{2V^2}{X_L}\frac{k}{(1-k)^2}(1-\cos(\delta)) \quad (9)$$

The reactive power injected by the GCSC can supply the reactive power demanded by the grid, and therefore it increases the line capacity of active power transmission.

It worth mentioning that distributed energy resources such as synchronous generators, batteries, micro-turbines, fuel cells, and photovoltaics can provide reactive power using their grid-coupling converter [45].

3.2 Voltage stability

Reactance compensation of the transmission line improves the voltage stability margins. When the inductance of the line decreases, the grid can handle more active power demand without a critical decrease in the voltage. This is shown in the following example.

Consider the equivalent circuit of a generation unit connected to the grid through an inductive transmission line, as shown in Fig. 9.

The current flowing from the sending end to the receiving end is

$$I = \left(\frac{E}{aX}\sin\delta\right) + \mathrm{j}\left(\frac{V - E\cos\delta}{aX}\right) \quad (10)$$

where a is the compensation coefficient of the line ($X_{GCSC} = (1-a)X_{T-Line}$). Therefore, the active and reactive powers at the receiving end are calculated as:

$$P_r = \frac{EV}{aX}\sin\delta \quad (11)$$

$$Q_r = -\frac{V^2}{aX} + \frac{EV}{aX}\cos\delta \quad (12)$$

If the equations are normalised with $v = V/E$, $p = P_rX/E^2$, and $q = Q_rX/E^2$, one obtains

$$p = \frac{v}{a}\sin\delta \quad (13)$$

$$q = -\frac{v^2}{a} + \frac{v}{a}\cos\delta \quad (14)$$

By squaring and adding (14) to the square of (15), a forth order equation is obtained for the voltage as

$$v^4 + (2qa - 1)v^2 + a^2(p^2 + q^2) = 0 \quad (15)$$

Considering that $q/p = k$, the normalised voltage of the receiving end is a function of the normalised value of active power at the receiving end, and it is shown by

$$v = \left((1 - akp) \pm \sqrt[2]{(0.25 - a^2p^2 - akp)}\right)^{0.5} \quad (16)$$

The normalised P–V curves of the system in Fig. 9, are shown in Fig. 10 for different levels of line compensation and $k = 0.25$. The

Table 1 Dualities of GCSC and TCR [33]

GCSC	TCR
switches in parallel with capacitor	switches in series with reactor
series connected in line	shunt connected to line
supplied by current source	supplied by voltage source
current of capacitor is controlled	voltage of reactor is controlled
voltage controlled by blocking angle of switches	current controlled by firing angle of switches
switches fired and blocked with zero voltage	switches fired and blocked with zero current

Table 2 Comparison of components rating of TCSC and GCSC [32]

Components	TSCS and GCSC comparison
voltage operation of the capacitor	operate with the same voltage
reactance of the capacitor	reactance of the capacitor is lower in the TCSC
current in the capacitor	current in the capacitor of the GCSC is always lower
valve currents	valve currents in the TCSC are higher where the ratio between the minimum and maximum impedances is lower than 0.5
valve voltage	valve voltage is lower in the TCSC

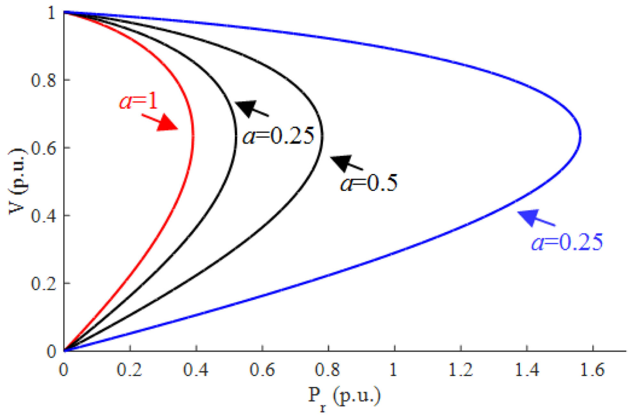
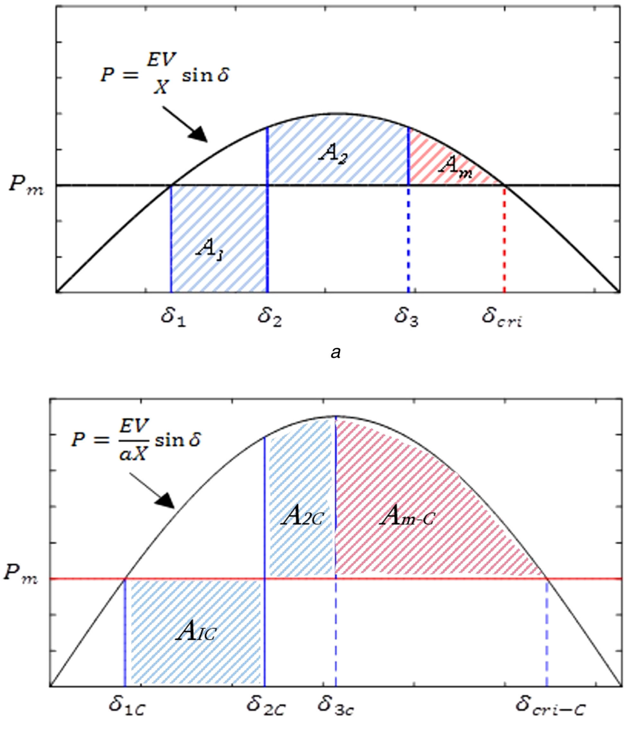


Fig. 10 *Voltage stability margins improvement using GCSC*



a

b

Fig. 11 *Transient stability improvement using GCSC*

parameter as shown in Fig. 10 is already defined as compensation factor.

As it is obvious, by increasing the level of compensation, the voltage stability margin increase. If the compensation was done using fixed series capacitors, the level of compensation would be limited due to the SSR. On the contrary, compensating the transmission line reactance using GCSC does not have this limitation, hence the voltage stability has wider margins.

3.3 Transient stability

To see the effect of GCSC on the transient stability of the system shown in Fig. 9, consider the power versus the angle of the system without and with series compensation, as shown in Figs. 11*a* and *b*, respectively. While the system is operating in normal condition, it delivers active power P_{me} at the angles of δ_1 and $\delta_{1\mathrm{C}}$, without and with series compensation, respectively. If a short-circuit fault occurs on the transmission line, no active power is delivered to the grid, but there is still mechanical power applied to the generation unit. Thus, the generator accelerates and its angles increase from the steady-state angles δ_1 and $\delta_{1\mathrm{C}}$ to δ_2 and $\delta_{2\mathrm{C}}$, respectively. If the faults were cleared, the electric power would be larger than the mechanical power, and consequently the generator would decelerate until reaching balance between energies. This would occur at the angles δ_3 and $\delta_{3\mathrm{C}}$, for the system without and with compensated line, respectively.

In the figures, the areas between P versus δ and the line corresponding to the constant power P_{me} over the intervals $[\delta_3, \delta_{\mathrm{cri}}]$ and $[\delta_{3\mathrm{C}}, \delta_{\mathrm{cri-C}}]$ represent the transient stability margins for the system without and with line compensation which are shown by A_{m} and $A_{\mathrm{m-C}}$, respectively. Also, A_1 and $A_{1\mathrm{C}}$ are equal to the kinetic energy and called accelerating areas, and A_2 and $A_{2\mathrm{C}}$ are equal to the increase in potential energy and called decelerating areas. As it is shown, this stability margin is considerably wider for the compensated line in comparison to the line without compensation because this stability area is proportional to the inverse value of the line reactance.

3.4 Power oscillation damping

Series FACTS compensator devices can contribute to damping power oscillations significantly by power transfer control over the transmission line. When a system experiences sudden load excursions, the generator accelerates or decelerates leading to a generator angle increase or decrease, respectively. To damp the resulting oscillations, the electric power should be equal to the input mechanical power of the generator. Consequently, when the angle of the generator increases, the electric power should increase as well. On the contrary, when the angle decreases, the electric power should also decrease to keep the power balance of the generator unit. Obviously, electric power control over the transmission line can be handled by the GCSC. When the generator speed increases, the capacitive reactance of the GCSC should increase by controlling the switching-off angle. When the generator speed decreases, the GCSC reactance should decrease to reduce the power transfer.

3.5 SSR damping

To show SSR in the presence of GCSC, consider the circuit of the GCSC as shown in Fig. 2.

The voltage across the capacitor is obtained by

$$C\frac{\mathrm{d}v_{\mathrm{C}}(t)}{\mathrm{d}t} = i(t) = i_{\mathrm{TL}}(t) - i_{\mathrm{SW}}(t) \qquad (17)$$

where $i_{\mathrm{TL}}(t)$ is the transmission line current, and $i_{\mathrm{SW}}(t)$ is the current of the power electronic switches. The current flowing through the anti-parallel switches depends on the time over which the switches are closed. Therefore, this current can be given by

$$i_{\mathrm{SW}}(t) = (1 - u(t))i_{\mathrm{TL}}(t) \qquad (18)$$

where u(t) is defined as:

$$u(t) = \begin{cases} 1 & \gamma \le t \le \pi - \gamma \\ 0 & \text{otherwise} \end{cases} \qquad (19)$$

Substituting (19) into (18)

$$\frac{\mathrm{d}v_{\mathrm{C}}(t)}{\mathrm{d}t} = u(t)\, i_{\mathrm{TL}}(t) \qquad (20)$$

The variable $u(t)$ can be expressed by its equivalent Fourier series as

$$u(t) = U_0 + \sum_{n=1}^{N} \frac{2n}{\pi}(\sin(n\delta)\cos(2n\omega_0 t)) \qquad (21)$$

where ω_0 is the fundamental frequency of the system. By neglecting the third and higher terms in (21), $u(t)$ is approximated as

$$u(t) = U_0 + U_1\cos(2\omega_0 t) \qquad (22)$$

in which, $U_0 = \delta/\pi$ and $U_1 = 2\sin\delta/\pi$.

The transmission line current can be formulated as the sum of the fundamental frequency current and the currents oscillating with sub- and super-synchronous frequencies. Thus, the transmission line current is expressed by

$$i_{\mathrm{TL}}(t) = -I_{\mathrm{TL}}\sin(\omega_0 t) + i_{\mathrm{osc}}(t) \tag{23}$$

When the transmission line reactance is not compensated, I_{osc}, which stands for the accumulated sub- and super-synchronous currents, is equal to zero ($I_{\mathrm{osc}} = 0$). However, when the line is compensated by constant or modulated series capacitors, sub-synchronous (ω_{sub}) and super-synchronous (ω_{sup}) current components appear, and the line current is

$$i_{\mathrm{osc}}(t) = -I_{\mathrm{sub}}\sin(\omega_{\mathrm{sub}}t) - I_{\mathrm{sup}}\sin\left(\omega_{\mathrm{sup}}t\right) \tag{24}$$

where ω_{sub} and ω_{sup} are defined as

$$\omega_{\mathrm{sub}} = 2\pi\left(f_0 - f_{\mathrm{tor}}\right) \tag{25}$$

$$\omega_{\mathrm{sub}} = 2\pi\left(f_0 + f_{\mathrm{tor}}\right) \tag{26}$$

and f_{tor} is the frequency of torsional oscillations. Two cases are considered:

Case i: $I_{\mathrm{osc}} = 0$. By substituting (24) into (21), the fundamental component of $v_{\mathrm{C}}(t)$ is obtained as

$$v_{\mathrm{C}}(t) = V_1\cos(\omega_0 t) \tag{27}$$

where

$$V_1 = \frac{I_{\mathrm{TL}}X_{\mathrm{c0}}}{\pi}(\delta - \sin(\delta)) \tag{28}$$

Case ii: $i_{\mathrm{osc}}(t) = -I_{\mathrm{sub}}\sin(\omega_{\mathrm{sub}}t) - I_{\mathrm{sup}}\sin\left(\omega_{\mathrm{sup}}t\right)$. By substituting I_{osc} in (21), the voltage of the capacitor is obtained as

$$\begin{aligned} v_{\mathrm{C}}(t) = {} & V_1\cos(\omega_0 t) + \left(U_0 + U_1\cos(2\omega_0 t)\right) \\ & \cdot \left(-I_{\mathrm{sub}}\sin(\omega_{sub}t) - I_{\mathrm{sup}}\sin\left(\omega_{\mathrm{sup}}t\right)\right) \end{aligned} \tag{29}$$

To simplify (29), the higher frequency components of the voltage are neglected, and only sub- and super-synchronous components are maintained, hence the capacitor voltage is represented by

$$\begin{aligned} v_{\mathrm{C}}(t) = {} & V_1\cos(\omega_0 t) + \frac{1}{C\omega_{\mathrm{sub}}}\left(U_0 I_{\mathrm{sub}} - \frac{U_1}{2}I_{\mathrm{sup}}\right) \\ & \times \cos\left(\omega_{\mathrm{sub}}t\right) + \frac{1}{C\omega_{\mathrm{sup}}}\left(-\frac{U_1}{2}I_{\mathrm{sub}} + U_0 I_{\mathrm{sup}}\right)\cos\left(\omega_{\mathrm{sup}}t\right) \\ = {} & V_1\cos(\omega_0 t) + V_{\mathrm{sub}}\cos\left(\omega_{\mathrm{sub}}t\right) + V_{\mathrm{sup}}\cos\left(\omega_{\mathrm{sup}}t\right) \end{aligned} \tag{30}$$

The relationship between the sub- and super-synchronous voltage components and the corresponding current components is given by

$$\begin{bmatrix} V_{\mathrm{sub}} \\ V_{\mathrm{sup}} \end{bmatrix} = \begin{bmatrix} \dfrac{U_0}{C\omega_{\mathrm{sub}}} & -\dfrac{U_1}{2C\omega_{\mathrm{sub}}} \\ \dfrac{-U_1}{2C\omega_{\mathrm{sup}}} & \dfrac{U_0}{C\omega_{\mathrm{sup}}} \end{bmatrix} \begin{bmatrix} I_{\mathrm{sub}} \\ I_{\mathrm{sup}} \end{bmatrix} \to V_{\mathrm{su}} = Z_{\mathrm{su}}I_{\mathrm{su}} \tag{31}$$

Even if the sub-synchronous current does not flow through the transmission line, sub-synchronous voltage appears in the capacitor due to the super-synchronous current. Considering the determinant of the impedance matrix ($\mathbf{Z}_{\mathrm{su}}$) in (31):

$$\det\left(\mathbf{Z}_{\mathrm{su}}\right) = \frac{\omega_0^2 \cdot X_{\mathrm{c0}} \cdot X_{\mathrm{C1}}(\delta) \cdot (\delta - \sin(\delta))}{\pi\omega_{\mathrm{sup}}\omega_{\mathrm{sup}}} \tag{32}$$

It is a positive value which sign never becomes negative. Therefore, the GCSC shows a capacitor behaviour, as expected.

If it is considered that the super-synchronous current is approximately equal to zero ($I_{\mathrm{sup}} \simeq 0$), then

$$V_{\mathrm{sub}} = \frac{\delta}{\pi C\omega_{\mathrm{sub}}}I_{\mathrm{sub}} = \frac{1}{C_{\mathrm{sub}}\omega_{\mathrm{sub}}}I_{\mathrm{sub}} \tag{33}$$

where

$$C_{\mathrm{sub}} = C_{\mathrm{eq}}\left(1 - \frac{\sin(\delta)}{\delta}\right) \tag{34}$$

In which C_{eq} is the effective capacitance of GCSC, and it is presented as

$$C_{\mathrm{eq}} = \frac{\pi C}{\delta - \sin(\delta)} \tag{35}$$

From (34) and (35), the GCSC modifies the effective capacitor from C_{eq} to C_{sub}, determining the resonance. Compared to a constant capacitor, the GCSC changes the resonance frequency to mitigate SSR oscillations. Accordingly, it may not be as effective as it should be, and using a supplementary controller to damp these oscillations have to be considered in designing the GCSC.

4 Future of GCSC

The shunt capacitors are better in different things specially power factor correction, reactive power support and economics. However, series capacitors can have another area such as controlling the voltage at the point of common coupling. Individually, such as unbalanced background voltage distortion and blocking harmonics strategies. In addition, series capacitive arrangement reduces the total reactive power loss by a large margin as compared to shunt capacitive arrangement [46]. A review of shunt capacitors can be an extension of current work.

Series-capacitor compensation is emerging as a stabilising tool in series compensation and phase shifting FACTS devices. Other applications include series power filters and large motor soft starting schemes. Hybrid use of series and shunt switched capacitors are now used in renewable energy converter DC–AC and AC–DC interface systems for energy efficient operation, voltage stabilisation and power quality enhancement.

GCSCs have been used extensively to enhance power flow and increase steady-state stability limits on congested overloaded transmission lines. In addition, fixed or switched series-capacitor banks in multi-stages are located at mid transmission lines or strategically placed to reduce congested feeders and reduce transmission losses. The devices are controlled by fast thyristors or GTO devices [47, 48]. Other applications include detuning resonance conditions or damping SSR to limit damage to steam turbine shafts.

New applications in HVDC schemes are required to limit harmonic instability triggered by AC–DC system interactions with DC-link control settings [49–51]. Future applications are emerging to facilitate interface of large wind schemes and PV farms to weak sub-transmission and transmission grids [52–55].

The use of GTO fast switching devices with new topologies has facilitated the integrated functions of series-shunt capacitor bank switching using modulated/switched filters and capacitive compensators for dynamic voltage stabilisation, loss reduction and flicker/inrush current control associated with large wind farm integration [56, 57].

Future applications are now extended to GTO-based series capacitor banks in distribution/utilisation grid systems for energy efficient and loss reduction for nonlinear-inrush type, cyclical and temporal loads [35, 58, 59].

Flexible soft computing control strategies and adaptive gain techniques using particle swarm optimisation, ant, harmony, bacteria foraging and weed invasion heuristic random search will improve dynamic response and scope of application [60–63].

The gate switched series capacitive compensation schemes using fast GTO thyristor and gate off schemes will continue to have a major role in long transmission lines to increase power transfer and reduce equivalent reactance, hence increasing both load ability and security of power transfer. Other applications are emerging in series–parallel filter switching to reduce inrush conditions and feeder losses in smart grid systems feeding large industrial motorised/Inrush loads. Emerging applications include smart distribution grid series–parallel switched capacitive banks for feeder loss reduction and power factor improvement at hybrid linear, motorised and non-linear loads [28].

5 References

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