On Harmonic Analysis of Multi – Module Gate - Controlled Series Capacitor (MGCSC) Considering SSR Phenomenon

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Abstract – The Gate – Controlled Series Capacitor (GCSC) is supposed to be an excellent transmission line series compensator. In practical applications, the GCSC would be used typically for EHV transmission lines compensation, requiring high power GTO valves. To overcome the limitations due to the power range of the GTO valves, multi-module GCSC (MGCSC) can be used in a way that several small GCSCs are connected in series with one another in order to provide the desired series compensation level. This paper presents a detail analysis and evaluation of the MGCSC while the special emphasis is given to the harmonic analysis of this device showing that how much of harmonic levels are generated by this device, and how they can be reduced. In addition, the harmonics of the power system, to where the MGCSC is connected, is studied. In order to consider the subsynchronous resonance (SSR) phenomenon, which is a potential problem in series compensated transmission lines, all analysis are performed in the IEEE First Benchmark Model, a highly unstable power system to SSR, by studying the impact of the MGCSC on the SSR mitigation.

Keywords: FACTS, Multi-Module GCSC (MGCSC), Power system harmonics, THD.

I. Introduction

INTERCONNECTED transmission systems are complex and require careful planning, design, and operation. The continuous growth of the electrical power system (especially large loads such as industrial plants), resulting in growing electric power demand, has put greater emphasis on system operation and control. In this scenario, series compensation of long lines is extensively applied to enhance power transfer and improve system stability. However, the use of series compensation may lead to sustained oscillations in generator–turbine shaft systems in thermal power stations closely connected to the compensated line. This phenomenon is known under the name “sub synchronous resonance” (SSR) [1]. Nevertheless, flexible ac transmission systems (FACTS) such as the static synchronous series compensator (SSSC) [2], [3], the static synchronous compensator (STATCOM) [4], the unified power flow controller (UPFC) [5], and the thyristor controlled series capacitor (TCSC) [6] have been used to avoid the SSR.

One of the FACTS controllers that recently has been introduced to be used as series compensation [7]-[9] and to damp the SSR [10]-[12] is the gate-controlled series capacitor (GCSC). The basic configuration of the GCSC is shown in Fig. 1. As seen in this figure, this device consists of a capacitor and a pair of GTO switches connected in anti-parallel. This device is inserted in series with the transmission line and by controlling the turn-off angle of the GTO switches, a part of the inductive reactance of the transmission line can dynamically be compensated.

The authors of the present work have presented some control methodologies for turn–off angle control of the GCSC [13]-[15] in order to damp the SSR in the GCSC.
equipped transmission line. Among them, a Takagi-Sugeno (TS) fuzzy logic controller was found to be the best controller for this device [16]. The proposed TS fuzzy controller uses a single GCSC to mitigate the SSR; however, in practical applications, the GCSC would be used typically for EHV transmission lines compensation, requiring high voltage GTO valves. To overcome the limitations due to the power rating range of the GTO valves, multi-module GCSC (MGSC) can be used in a way that several small GCSCs can be connected in series with one another to provide the desired GCSC rating for a determined series compensation level [17]. Also, since in the MGSC the power rating of the total GCSCs are reduced, utilizing this configuration can dramatically decrease the total cost of project and consequently can be a very cost-effective solution for the series compensation and SSR mitigation. Fortunately, the GCSC is a zero voltage switching (ZVS) device, i.e. the GTO’s are always turned on and turned-off at the zero voltage [16]. Thus, the series connections of the GTO’s are not difficult. In addition, utilizing the MGSC can mitigate the harmonic levels which may be harmful to the system where the GCSC is connected and may limit the total amount of the series compensation.

In this article, the MGSC is evaluated and analyzed while the special emphasis is given to the harmonic analysis of the MGSC voltage. It is shown that the harmonic levels can be mitigated by increasing the number of modules in the MGSC while this increase does not threaten the system to the SSR phenomenon. Also, the harmonics of the power system, to where the MGSC is connected, is analyzed. It is shown that the total harmonic distortion (THD) of the line current increases after fault, and at longer times the current will lose its sinusoidal waveform at the fundamental frequency of 60 Hz.

## II. Investigated System

Fig. 2 shows the “IEEE First Benchmark Model” (FBM) [20], including the MGSC with n modules. This model is composed by a synchronous generator connected to an infinite bus via a compensated 500 kV transmission line. The transmission line is represented by $\frac{1}{R_L} \cdot X_L$ and $\frac{1}{X_P}$ when the MGSC works in its off-line Mode. The mechanical system consists of a four-stage steam turbine, the generator, and a rotating exciter.

### II.1. Series Compensation in off-line MGSC Mode

The SSR phenomenon is investigated for the case that the system is tuned at torsional mode 1, based on Table I. In this section, the MGSC in Fig. 2 works in its off-line Mode and the series compensation is performed just by the fixed series compensation, $X_c=0.472$ p.u.

To excite the torsional modes of the system, a three phase short circuit was applied at point B in Fig. 2 at $t=1$ s. Fig. 3 shows the unstable measured transmission line current for this case. This figure shows that the main oscillation occurs at around 15.5 Hz which is the frequency of the torsional mode 1, as given in Table I. Also, in Fig. 4, the total harmonic distortion (THD) of the transmission line current as function of time is presented. As seen in this figure, the THD of the line current increases after fault, and at longer times the current will lose its sinusoidal waveform at the fundamental frequency of 60 Hz.

In Fig. 5 the generator terminal voltage when the MGSC works in off-line Mode is compared with the voltage when the MGSC is working in on-line Mode.
shown. This figure shows that in off-line MGCSC Mode, the generator terminal voltage is severely distorted.

Fig. 3. The measured transmission line current for off-line MGCSC Mode.

Fig. 4. Total harmonic distortion (THD) of the measured current for off-line MGCSC Mode as function of time.

Fig. 5. The generator terminal voltage for off-line MGCSC Mode.

III. Multi – Module GCSC (MGCSC)

III.1. Principle of operation

The Gate-Controlled Series Capacitor (GCSC) is a very simple device with probably the simplest configuration among all FACTS devices. A single GCSC consists of a main capacitor and two GTOs connected in anti-parallel. The principle operation of this device is quite simple. It is controlled by varying the turn-off angle ($\gamma$) of the GTOs. The GCSC is zero-voltage switching (ZVS) equipment, that is, the GTOs always turn on and off at zero voltage, which significantly reduces the switching losses. Also, being ZVS device, several single GCSCs can easily be connected in series with one another in order to provide the desired series compensation level called the MGCSC. Fig. 6 shows the principal current and voltage-waveforms for one of the MGCSC modules.

If all the switches are kept turned-on all the times, the reactance of the MGCSC is bypassed, and there is no compensation by this device. However, when all or some of the switches are turned-off once per cycle, at a given turn-off angle ($\gamma$) counted from the zero crossing of the transmission line current, the MGCSC capacitor turns-on and off alternatively in series with the transmission line, and a voltage appears on the MGCSC. The compensation level of the MGCSC is determined by adding the fundamental component of the voltage ($v_c$) on the each Module of the MGCSC. In this study, it is assumed that all the MGCSC modules have the same reactance, and they are turned-on and off simultaneously. With these assumptions, the relationship between the equivalent capacitive reactance of each module of the MGCSC and turn-off angle ($\gamma$) is given by [16]:

$$X(n, \gamma) = \frac{(X_C/n)}{2\pi\gamma} (2\gamma - 2\pi - \sin(2\gamma))$$

(1)

Therefore, the equivalent reactance of the MGCSC is calculated as follows:

$$X(\gamma) = X(n, \gamma) \cdot n$$

(2)

Fig. 7 shows the nonlinear relationship between the equivalent capacitive reactance of the MGCSC and the turn-off angle ($\gamma$). At the fundamental frequency, the MGCSC is equivalent to a continuously variable series.
capacitor, where its reactance varies from its maximum value (1 p.u) for \( \gamma = 90^\circ \) to the minimum value (0 p.u) for \( \gamma = 180^\circ \).

### III.2. Series Compensation With The MGCSC

For series compensation with the MGCSC, this device in Fig. 2 becomes on-line, and series compensation is carried out as the MGCSC with different number of modules plus a fixed series capacitor. The total capacitive series compensation was made equal to 0.472 p.u. just to try to excite the SSR at mode 1, as given in Table I. In the present study, the ratio between the equivalent reactance of the MGCSC and the fixed series compensation is considered 1:3. This means that for mode 1, out of a total of 0.472 p.u. of capacitive reactance, 0.152 p.u. will be provided by the MGCSC with any number of modules and 0.318 p.u. will be provided by the fixed capacitor, \( X_{fc} \).

To determine the steady state MGCSC equivalent reactance (0.152 p.u.), depending on \( n \), \( X_C \), and \( \gamma \); there are many different states. In this study, for increasing the maneuverability of the MGCSC equivalent reactance, especially in the fault conditions, the steady state turn-off angle (\( \gamma \)) is chosen in such a way that the MGCSC equivalent reactance is at the middle of the entire variation range between \( X(90^\circ) \) and \( X(180^\circ) \) as seen in Fig. 7. By this way, the steady state turn-off angle is calculated about 113.5° and then the MGCSC equivalent reactance can be verified in (1) and (2) by choosing a proper values of \( n \) and \( X_C \).

### IV. Harmonic Analysis of MGCSC

#### IV.1. Single MGCSC (GCSC)

As seen in Fig. 6, the voltage waveform in the GCSC contains both the fundamental component and the higher order harmonics. If the GCSC is operating in the steady state condition, the positive half-cycle of the GCSC voltage has the same shape as the negative half-cycle. Also, because the voltage waveform of the GCSC is symmetrical to the time axis, it contains only odd harmonics that is given by:

\[
V_j(\gamma) = \frac{4V_{Max}}{\pi} \left( \frac{0.5 \sin((j+1)\gamma) + j+1}{0.5 \sin((j-1)\gamma) - \cos \gamma \sin(j\gamma) / j} \right) 
\]

In Fig. 8, the harmonic orders of the GCSC voltage up to the 13th harmonic order are depicted as function of the turn-off angle. In this figure, the voltages are in p.u. and the \( V_{Max} \) is assumed to be the base value. As seen in this figure, the harmonic orders vary by the turn-off angle varying, and they have maximum values at the different values of the turn-off angle. For example, the 3rd and 5th order harmonics have a maximum of about 0.14 p.u. and 0.12 p.u., respectively when the turn-off angle is respectively 119° and 109°. Also, as mentioned before, the steady state turn-off angle in this paper is chosen 113.5°, and the harmonic orders in this degree can be obtained using Fig. 8. As seen in this figure, the maximum harmonic order in this degree is the 3rd having the amount of approximately 0.13 p.u.

The GCSC voltage total harmonic distortion (THD) is determined based on the system voltage, instead of the maximum value of the GCSC voltage [17]. Thus, the THD of the GCSC is given by:

\[
THD = \frac{4V_{Max}}{\pi V_{Rated}} \sqrt{\sum V_j(\gamma)^2} \quad j = 3, 5, 7, ...
\]

To study the THD as a function of turn-off angle, suppose that the single GCSC maximum voltage \( V_{Max} \) in 100% compensation is 0.6 p.u of the rated voltage of the system, i.e. \( V_{Max} / V_{Rated} = 0.6 \). In this case, the THD as a function of turn-off angle is shown in Fig. 9. As seen in this figure, at the rated voltage of the system, the single GCSC voltage THD may have values higher than 5%. The harmonic level in the GCSC may be so harmful for the system to where the GCSC is connected and may limit the line compensation. To reach to an acceptable THD in the GCSC voltage, the MGCSC can be used as series compensation while because the power rating of the GTO valves are reduced in the MGCSC, it is more cost-effective than the single GCSC.
IV.2. Multi Module GCSC (MGCSC)

Utilizing the MGCSC, depending on the number of GCSC modules, the maximum voltage on each GCSC modules ($V_{\text{Max}}$) can be reduced; consequently, the THD of the GCSC voltage is decreased as can be verified in (4). It is again assumed that the maximum single GCSC voltage is 0.6 p.u. of the system rated voltage. Then, the number of modules increases from 2 to 10 modules. The MGCSC voltage THD for different number of modules is shown in Fig. 10. As seen in this figure, when the number of modules increases, the MGCSC voltage THD decreases. This figure also shows that the minimum THD is obtained about 0.8 % for the MGCSC with 10 modules which is well below the permissible limit recommended in the related standards [18]-[19].

![Fig. 10. Impact of increasing the number of modules on decreasing the MGCSC voltage THD.](image)

V. MGCSC turn–off angle Controller Design

In this section, the turn-off angle controller design of the MGCSC is presented. This controller is based on the TS fuzzy controller which is shown in Fig. 11. As seen in this figure, the power calculation block diagram calculates the line real power. This measured power is then passed through a first order low-pass filter (LPF) and a band-pass filter (BPF). The LPF with cutoff frequency of 3 Hz is for diagnosing of the electromechanical power oscillation in the line real power. Also, the BPF allows only passing of the electrical power oscillations with frequencies between 3 and 20 Hz, which the torsional mode 1 (15.75 Hz) is in this interval. The diagnosis of the SSR in the line power is the duty of this filter. The outputs of these two filters are compared with a power order, and then are used as TS fuzzy logic controller inputs, namely $X_1$ and $X_2$, respectively. The output of the TS fuzzy controller ($Y$) is the MGCSC turn-off angle that after passing through a limiter, is fed to a pulse generator block synchronized with the line current zero crossing to get the GCSC input final pulse. Also, in Fig. 11 there is an operation mode selector to prepare ability of setting manual constant turn-off angle.

VI. Results and Discussion

VI.1. SSR Analysis

A MGCSC with 10 modules became on-line in Fig. 2 and the system was tuned to the torsional mode 1, based on Table I. To verify the impact of the MGCSC on SSR mitigation, a three phase short circuit was applied at point B in Fig. 2 at t=7.5 s with 0.1 s time duration to excite the torsional mode 1 of the system. The measured transmission line current for the MGCSC with 10 modules is shown in Fig. 12 where the fault current increases to about 1.8 p.u. As seen in this figure, the SSR appears in the system after applying the three phase short circuit at frequency around 15.5 Hz, as given in Table I; however, these oscillations are damped in less than 0.1 sec utilizing the designed TS fuzzy controller. This figure also shows that a low frequency oscillation (LFO) appears in the system at frequency around 2 Hz, as shown in Table I, which is damped in less than 2.5 s. In addition, the applied turn-off angle by the TS fuzzy controller to the MGCSC is shown in Fig. 13. This figure shows that the turn-off angle settles to its steady state ($\theta_{_5} = 113.5^\circ$) after fault. In Fig. 14 the generator terminal voltage is shown. As seen in this figure, contrary to Fig. 5, when the MGCSC works in its off-line Mode, the generator terminal voltage approximately does not experience any voltage distortion, and it is quickly compensated by the MGCSC.

The system were also examined for the MGCSC with the different number of modules and the obtained results showed that the number of modules has no effect on the MGCSC dynamic and performance in SSR and LFO damping, and the MGCSC with the different modules as well as a single GCSC have approximately the same behavior in SSR and LFO mitigation. Also, there is no need to deregulate the parameters of the TS fuzzy controller for different modules. Hence, without concerning about the SSR phenomenon, the number of modules can be increased up to the desired number in order to achieve the desired MGCSC rating for the desired series compensation level. This makes it possible to use GCSCs with lower power ratings. As a result, the power rating of the GTO switches can be decreased resulting in an applicable and lower-cost configuration for series compensation and SSR damping by the MGCSC.

VI.2. Harmonic Analysis of MGCSC Voltage

It has been already shown that the number of MG-
CSC can be increased up to the desired number without concerning about the SSR phenomenon. Also, in section IV, it was shown that increasing the number of modules decreases the MGCSC voltage THD. In this subsection,
VI.3. Power System Harmonic Analysis

The total harmonic distortion (THD) is an important figure of merit used to quantify the level of harmonics in voltage or current waveforms. Accordingly, standards, such as IEEE 519 [18] and IEC 61000 [19], specify the limit for the THD in the voltage and the current. In this section, the harmonics of the transmission line current and the generator terminal voltage are analyzed for the MGSC with 10 modules. Fig 19 shows the THD of the line current and the generator terminal voltage as a function of time. For constant series compensation, as seen in Fig. 4, after fault the THD of the line current increases with time, and in fact, the line current loses its sinusoidal waveform at longer times; however, as seen in Fig. 19, utilizing the MGSC, the THD of the line current and the generator terminal voltage for all the times before and after fault, except during fault for about 0.1 sec, are well below the permissible limit recommended in the aforementioned standards. In addition, the harmonic spectra of the generator terminal voltage and the line current are shown in Figs 20 to 21, respectively. These figures show that the level of harmonic orders in the line current and the generator terminal voltage are trifle, and consequently it can be deduced that approximately there is no harmonic pollution on the power system to where the MGSC is connected.

VII. Conclusion

This paper presents a harmonic analysis of the multi-module Gate-Controlled Series Capacitor (MGSC) operating in a highly unstable series compensated power system to damp the subsynchronous resonance (SSR) phenomenon. It was shown that the single GCSC produces a high content of voltage harmonics. Also, in practical applications, the GCSC with high power rating is needed. To overcome the limitations due to the power rating range of the GTO valves and to reduce the harmonic levels in the voltage of the GCSC, the MGSC was placed in the IEEE First Benchmark Model to compensate a part of transmission line inductive reactance. It was shown that without concerning about the SSR phenomenon, the number of modules can be increased up to desired value in order to provide the desired series compensation level resulting in more cost effective configuration than the single GCSC. Also, increasing the number of modules can decrease the
harmonic levels in the MGCSC voltage.

In addition, the harmonics of the MGCSC equipped power system were evaluated. The obtained results showed that there is approximately no harmonic pollution in the transmission line current and the generator terminal voltage arising from the MGCSC.

References


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