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THE EFFECT OF A STATIC SYNCHRONOUS SERIES COMPENSATOR ON TRANSIENT PROPERTIES OF THE SYSTEM

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Examiners: Professor Jarmo Partanen
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ABSTRACT

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The effect of a Static Synchronous Series Compensator on transient properties of the system

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Abstract

Developments in the power converter technology field create the prerequisites for the emergence of flexible alternating current transmission systems of the second-generation devices, namely the advent of transformerless static synchronous serial compensator (SSSC). These technologies enable to extend the application of the series connected FACTS devices to increase the transmission capacity of lines and to improve the system controllability. Thus, the integration of this appliance provides an opportunity to overcome many technological limitations. In this regard, the purpose of this master's thesis is to study the impact of the SSSC on operation modes and transient processes in the electric power system, namely the effect of SSSC control gains on the steady-state and transient stability. Results of mathematical modeling have shown the detrimental influence of the SSSC negative current proportional gain on critical fault clearance time. Therefore, with these controller settings, the facility should be switched out of operation or into a mode with a positive sign, which favorably affects the stability by increasing fault clearance time. Steady-state stability analysis was performed for tuned regulator channels, which were optimized using two methods: D-decomposition and simultaneous coordination of controller settings. Where was obtained that the same damping degree can be achieved for different current control channel values with corresponding changes in the regulator channels on generator rotor slip or voltage frequency at the connection point.

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SYMBOLS AND ABBREVIATIONS

Abbreviations

AR	Automatic regulator
AER	Automatic excitation regulator
BJT	Bipolar Junction transistor
EMF	Electromagnetic force
EPS	Electric power system
FACTS	Flexible Alternating Current Transmission Systems
GCSC	GTO Thyristor-Controlled Series Capacitor
GTO	Gate turn-off
IB	Infinite bus
IGBT	Insulated gate bipolar transistors
IGCT	Integrated gate-commutated thyristors
MCC	Main control channel
MOSFET	Metal–oxide–semiconductor field-effect transistor
PWM	Pulse-width modulation
SC	Short-circuit
SM	Synchronous machine
SSSC	Static Synchronous Series Compensator
STATCOM	Static synchronous compensator
TCSC	Thyristor-Controlled Series Capacitor
TCR	Thyristor-controlled reactor
TSSC	Thyristor-Switched Series Capacitor
VSC	Voltage-source converter

Symbols

E_q	*quadrature-axis synchronous stator electromotive force*
E_Q	*auxiliary stator electromotive force when* $x_d \neq x_q$
E_q''	*quadrature-axis component of subtransient electromotive force*
E_d''	*direct-axis component of subtransient electromotive force*
ψ_d	*direct-axis stator flux linkage*
ψ_q	*quadrature-axis stator flux linkage*
ψ_r	*field flux linkage*
ψ_{rd}	*direct-axis amortisseur flux linkage*

ψ_{rq}	*quadrature-axis amortisseur flux linkage*
ψ_{ad}	*direct-axis mutual flux linkage (between stator and rotor)*
ψ_{aq}	*quadrature-axis mutual flux linkage (between stator and rotor)*
u_d	*direct-axis stator terminal voltage*
u_q	*quadrature-axis stator terminal voltage*
u_f	*field voltage*
i_d	*direct-axis stator current*
i_q	*quadrature-axis stator current*
i_r	*field current*
i_{rd}	*direct-axis amortisseur current*
i_{rq}	*quadrature-axis amortisseur current*
r	*stator resistance*
r_r	*field resistance*
r_{rd}	*direct-axis amortisseur resistance*
r_{rq}	*quadrature-axis amortisseur resistance*
ω_s	*synchronous frequency*
x_d	*direct axis synchronous reactance*
x_q	*quadrature axis synchronous reactance*
x_{ad}	*direct-axis mutual reactance (between stator and rotor)*
x_{aq}	*quadrature-axis mutual reactance (between stator and rotor)*
x_s	*stator leakage reactance*
x_{sr}	*field leakage reactance*
x_{srd}	*direct axis amortisseur leakage reactance*
x_{srq}	*quadrature axis amortisseur leakage reactance*
T_J	*mechanical inertia constant*
M_t	*torque moment*
M_e	*electromagnetic moment*
δ	*angle between rotor quadratic axis and stator voltage*
s	*rotor slip*
I_{set}	*current setting value*

K_{0i}	*current proportional gain*
T_i	*time constant of current deviation channel*
T_{SSSC}	*time constant of SSSC*
I_{dreg}	*direct-axis SSSC current*
I_{qreg}	*quadrature-axis SSSC current*
T_{os}	*time constant of slip deviation channel*
T_{of}	*time constant of frequency deviation channel*
K_{os}	*slip proportional gain*
K_{of}	*frequency proportional gain*
T_{1s}	*time constant of slip derivative channel*
T_{1f}	*time constant of frequency derivative channel*
K_{1s}	*slip derivative gain*
K_{1f}	*frequency derivative gain*
K_{0u}	*voltage proportional gain*
K_{1u}	*voltage derivative gain*
K_{0w}	*frequency proportional gain*
K_{1w}	*frequency derivative gain*
K_{1if}	*current field winding derivative gain*
Δt_{SC}	*critical fault clearance time.*

Chapter 1.

Introduction.

The expansion of the power grid complex and the implementation of the renewable energy sources result in the increased complexity of electrical power systems (EPS). Moreover, the introduction and deployment of new technologies complicate the networks control specifically in disturbance situations. As a consequence, in the energy developed countries, flexible alternating current transmission systems (FACTS) are being introduced, which allow to solve complex tasks of ensuring the required stability and reliability indicators of the power system, as well as reducing the total cost of electric power transmission by excluding new network construction.

Series connected FACTS appliances contribute to the rise of the electric power transmission system transfer capacity. A static synchronous series compensator (SSSC) is a solid example. At present, there is a growing interest in the development and implementation of these technologies, as they allow to avoid cable replacements of existing transmission lines or the construction of new overhead power lines. This is due to the fact that the complexity and cost of construction of new transmission lines are increasing caused by the introduction of private land ownership rights and stricter environmental requirements for construction. In addition, the series-connected compensating devices allow to increase the controllability of the network and eliminate bottlenecks in the power system, as well as to ensure the output of locked capacities.

Since the SSSC is an “active” control facility, it is also one of the means to increase the stability of the EPS. The question of ensuring energy system stability becomes the object of special attention. As this question is the key one in studying the problems of electromagnetic and electromechanical transient processes, where the stability of the EPS reflects the ability of the system to return to original or other operational acceptable modes of operation after the infinitesimal or finite disturbance.

The integration of devices based on the use of power converter technology with digital control systems enables significantly abandon many technological limitations that lead to lower reliability. Thus, the SSSC performs the following functions in the EPS:

1. Improving the quality of the voltage level in the system,
2. Continuous maintenance of the necessary degree of compensation,
3. Damping of electromechanical oscillations,
4. Flexible and stepless control of active and reactive power flows up to the achievement of the thermal limit in power transmission lines,
5. Optimization of active power distribution between parallel lines, and as a consequence reduction of losses,
6. Increase of transfer capacity by compensation of line reactance,
7. The number reduction of parallel lines by decreasing the cost of electricity transmission.

The relevance of this master's thesis work is that it provides challenging opportunities for the SSSC device to be implemented in the power system. JSC "LENENERGO" in Russia considers the use of the FACTS equipment to eliminate bottlenecks in the 110 kV network. The JSC "LENENERGO" network has 60 points of forced gap due to the excess of steady-state mode continuous current carrying capacity and short circuit current capacity. Therefore, the result of this work can be used when considering these tasks.

In connection with the development and growth of the SSSC device applications, the task of evaluating the efficiency of this technology is relevant. Consequently, the following issues were considered in this work:

The first chapter provides an overview of the SSSC equipment's main components, its configuration, and its control. In addition, SSSC was compared with other series compensation devices and the main advantages of the studied facility were described.

The second chapter describes a mathematical model of the researched power transmission scheme, specifically the model of a synchronous generator with automatic excitation regulation and a quick-operating series valved device – SSSC.

The third chapter considers tasks related to the increase of power transmission line controllability and the study of transient stability. The main regularities of the SSSC influence on the power transmission operation mode have been analyzed and the effect on critical fault clearance time at different regulator coefficients have been studied.

The fourth chapter reflects the assessment of the series control device influence on oscillation damping of the single electricity transmission system. Coefficient optimization of the synchronous generator automatic excitation regulator of strong action and SSSC regulator was made.

In conclusion, the work’s main summary was made.

The modeling of the SSSC device and transient processes calculations were performed in Dymola software. While the optimization of parameters of synchronous generator and SSSC regulators was conducted in MATLAB software.

Chapter 2.

Components and operation principles of SSSC

A SSSC is a series compensating device based on the use of the power converter technology as a synchronous voltage source – Figure 2.1. The main function of this facility is to generate voltage vector with the controllable magnitude and phase in quadrature with a line current. If the generated voltage lag by 90°, the voltage drop created by a line's series impedance is compensated. In the opposite case (lead by 90°), the additional voltage drop is produced. (Eremia, et al., 2016)

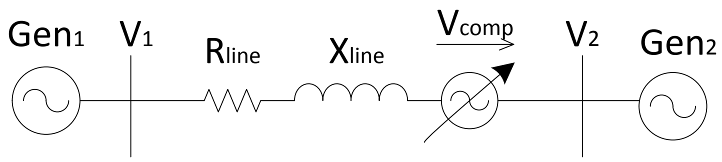


Figure 2.1. SSSC schematic diagram

2.1.Power electronics in SSSC

Principal tasks of SSSC devices are to control the power flow in the line and to ensure stable operation of the network at different disturbances. To implement these functions, the equipment must have a rapid response.

Second generation FACTS equipment owe their origin to high voltage, high current and high-speed element base – insulated gate bipolar transistors (IGBT), gate turn-off (GTO) thyristors, and integrated gate-commutated thyristors (IGCT).

2.1.1. IGBT

IGBT combines the best qualities of bipolar junction transistors (BJT) and metal–oxide–semiconductor field-effect transistors (MOSFET), which are a high impedance gate and high switching frequency (MOSFET) with the low on-state voltage of a BJT. The high impedance gate value ensures that the small amount of energy required to turn-on or turn-off the device. This type of transistor is capable of withstanding high values of collector-emitter current with particularly zero gate current drive. (Mohan, et al., 1995) (Hingorani & Gyugyi , 2000)

The IGBT is a voltage-controlled device, therefore, only a small voltage value is needed to maintain the conductive state. It should be noted that IGBT is a unidirectional technology. Current switching is only possible in the forward direction. The characteristic of the IGBT transistor is shown in Figure 2.2. (Mohan, et al., 1995).

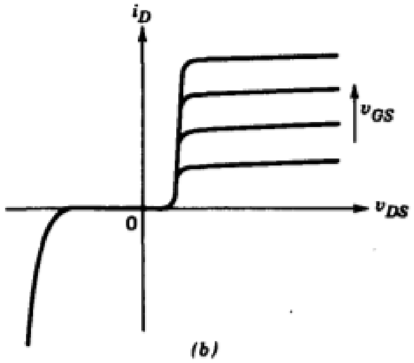


Figure 2.2 Idealized IGBT characteristic

Gate voltage control provides the current-limiting capability. However, this mode is characterized by quite high losses. Moreover, for high power installations, only for a short period of time (a few microseconds) this current-limiting mode can be utilized. Nevertheless, this time period ensures enough time to undertake protection actions. This characteristic is particularly useful for voltage-sourced converters (VSC). Since the large DC capacitor connected across the converter, the short-circuit current can rapidly rise to high values. (Hingorani & Gyugyi , 2000)

The main merits of the IGBT are its ability to handle voltages with the value of more than 1000 V, high switching frequency (from 1 to 100 kHz), low switching losses, and current-limiting capability. In addition, IGBT has an essential advantage over GTO thyristors: the transistor is not latching into a conductive state, therefore the transition to a closed state is fully gate controlled. All the above features make the IGBT transistor an excellent choice for devices such as pulse-width modulation (PWM) (Eremia, et al., 2016) (Mohan, et al., 1995) (Hingorani & Gyugyi , 2000).

2.1.2. GTO thyristors

Conventional thyristors can only be converted to a non-conductive state when the anode current is reduced to zero, but GTO thyristors have a structure that allows them to be switched to a non-conductive state by applying a negative gate-cathode voltage, which results in a large value of negative gate current. The current flows only for a few microseconds, but its amplitude must be about one-third of the anode current in order to switch to the non-conductive state. This results in significant energy loss during the turn-off process. The energy used for locking is 10-20 times higher than the energy used for opening. (Mohan, et al., 1995; Hingorani & Gyugyi , 2000)

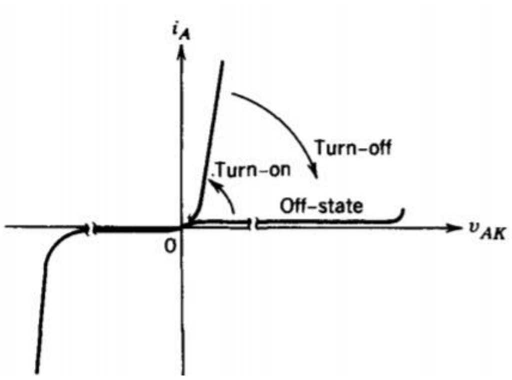


Figure 2. 3. Idealized characteristic of GTO thyristor

Turn-on conditions for GTO thyristors are the same as for conventional thyristors. It is a short pulse of gate current. The conductive state is maintained even after the removal of the pulse. The characteristic of the GTO thyristor is shown in Figure 2. 3. (Mohan, et al., 1995)

In most cases, GTO thyristors are used in VSC, where the rapidly recovering diode is connected in the opposite direction to each GTO thyristor. In addition, GTO requires a snubber circuit connected in parallel in order to withstand the large du/dt that accompanies the inductive elements switching off. (Mohan, et al., 1995; Hingorani & Gyugyi , 2000; Eremia, et al., 2016)

It should be noted that GTO thyristors have a low voltage drop in the conductive state, 50% lower than IGBT. However, the main disadvantage of the GTO thyristor compared to IGBT is the high requirements to the turn-off drive, which in turn leads to long turn-off time, lower di/dt and dv/dt capability, and thus to expensive snubber circuits. (Hingorani & Gyugyi , 2000)

Due to their ability to withstand significant values of voltages (up to 4.5 kV) and currents (up to several kA), with switching frequency up to 10 kHz, GTO thyristors are used as the main control device in converters.

2.1.3. IGCT

It would be a great benefit if the device had a low voltage on-state value (as for thyristors) and at the same time had low gate drive requirements and fast turn-off time (as for IGBT transistors). In fact, these technologies exist. They are GTO thyristors with improvements that meet the requirements of the modern power electronics integration concept. They reduce the gate drive requirements and ensure high switching speeds. Such devices include the IGCT. (Hingorani & Gyugyi , 2000; Eremia, et al., 2016)

IGCT is a switch with turning-off capabilities that goes into a non-conductive state as a transistor, but in a conductive state has the characteristics of a thyristor. However, the ability to turn-off results in higher conductive losses compared to conventional thyristors.

The main advantages of IGCT are low resistance in the open state, high switching currents and voltages, low power consumption of the control circuit, and the ability to open and to close. It should be noted that IGCT requires a snubber circuit with lower requirements to protect against excess du/dt. (Eremia, et al., 2016). Compared to GTO thyristors, IGCT can reduce the turn-off time (approx. 30 times) as well as the conductivity losses. IGCT also has a higher pulse current capability than IGBT. However, in a situation where the thyristor current rises above the permissible values, the time to disconnect the inverter from the input power supply will be a thousand times longer (several milliseconds). (Eremia, et al., 2016; ABB, -)

2.2.Voltage-source converters in SSSC

The operating principle of SSSC is implemented on the VSC basis, which uses power rectifier valves. Rectifier valves regulate the output voltage of the device. (Eremia, et al., 2016)

The H-bridge circuit (Figure 2. 4) is often used in the SSSC (Smart Wires, 2020). The converter consists of two half-bridge circuits connected in parallel in the DC side. Each leg group of converter includes two switches and their diodes, which are connected in antiparallel. When switch S is open, either switch S or diode D conducts current, depending on its direction. Switches from one leg group (S1, S4) and (S3, S2) never conduct simultaneously, otherwise, it creates the condition for short-circuit current to flow. The DC side voltage is normally fixed while the voltage on the AC side is adjusted. (Eremia, et al., 2016) (Mohan, et al., 1995) (Wu, 2006)

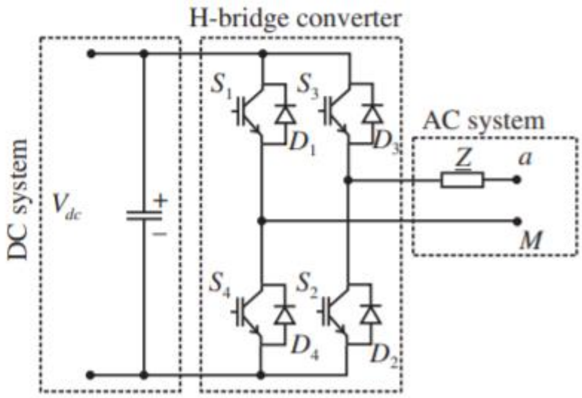


Figure 2. 4. Simplified H-bridge scheme (Eremia, et al., 2016)

PWM is used to improve output voltage quality. It generates a quasi-sinusoidal wave with a dominant first harmonic frequency. PWM allows both the phase and amplitude of the generated voltage to be changed. (Hingorani & Gyugyi , 2000)

In PWM, a modulating signal varying with the frequency of the output voltage is compared to a repetitive triangular or sawtooth-shaped signal -Figure 2. 5. A single or zero bit is generated from the comparison. The PWM output signal is a square waveform alternating signal with pulses of unequal width. The first harmonic frequency can be distinguished in the output signal. The frequency of the triangular signal determines the switching frequency, and the changes in the amplitude of the modulating signal determine the corresponding changes in the amplitude of the output signal (Mohan, et al., 1995) (Eremia, et al., 2016).

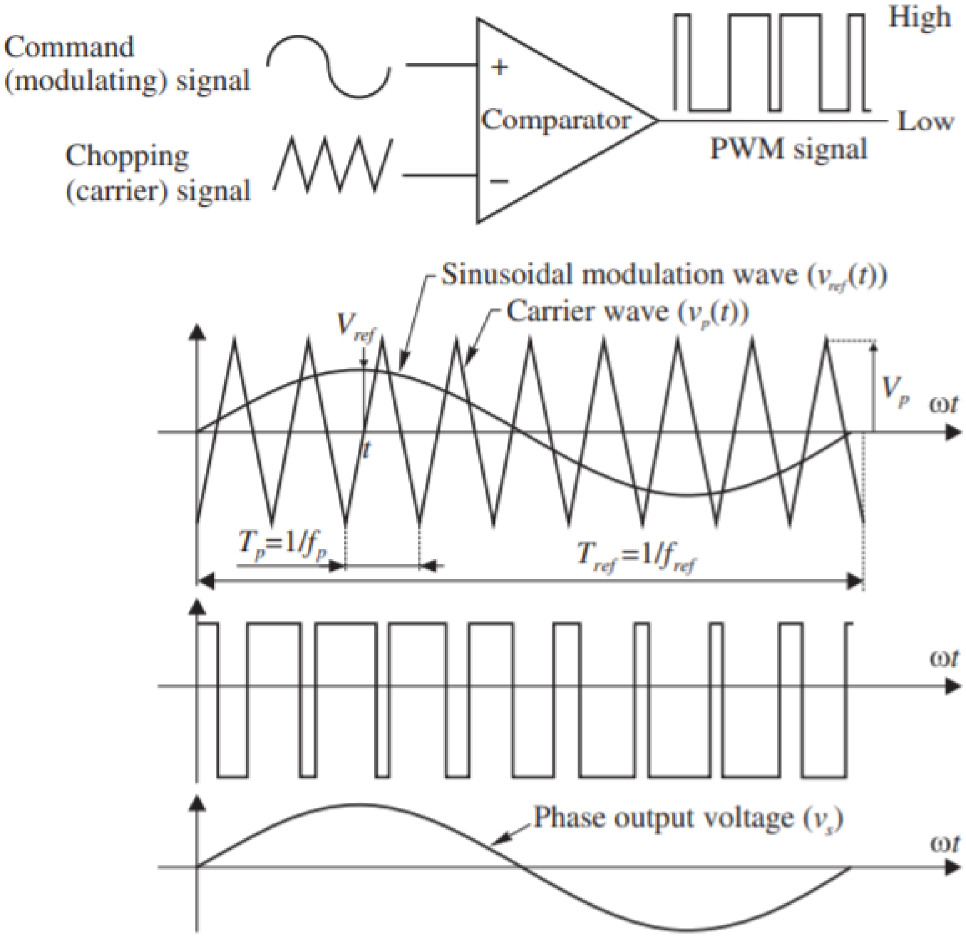


Figure 2. 5. Sinusoidal PWM (Eremia, et al., 2016)

The type of generated PWM signal can be unipolar and bipolar. It should be noted that a unipolar signal type has a lower harmonic content (Mohan, et al., 1995) (Wu, 2006).

2.3.Operating principle of the SSSC

SSSC is a modern FACTS device based on VSC connected in series with the power line through the transformer. A SSSC operates as a controlled serial capacitor or inductance. A special feature of the SSSC is that the injected voltage is independent of the current flowing through the line and can be controlled independently. This feature allows sufficiently operation with both low and high loads. By changing the voltage compensation in the line, the SSSC controls the transmitted power. (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016) (Padiyar, 2007)

The SSSC is capable of generating both active and reactive power to the grid, thus, compensating for the voltage drop in the active and reactive elements. To be able to control active power flow a relatively large power source is required. Thus, this is an expensive device. Without an additional power source, the SSSC can only generate the voltage that leads or lags the current by 90°. (Hingorani & Gyugyi , 2000)

The reactance of the line is constant but can be virtually varied with the voltage inserted into the line. By changing the polarity of the generated voltage (Figure 2.6), the resulting voltage can increase or decrease in the power line. In the case of serial capacitive compensation (insertion of a voltage vector lagging behind the current), the equivalent line impedance is reduced, and as a result, the power limit of the overhead transmission line is increased. In the case of serial inductive compensation (generation of a voltage vector leading the current), the equivalent line impedance is incremented, and the power limit is decreased. Therefore, the SSSC provides both capacitive and inductive compensation due to the ability to change the polarity of the generated output voltage. (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016)

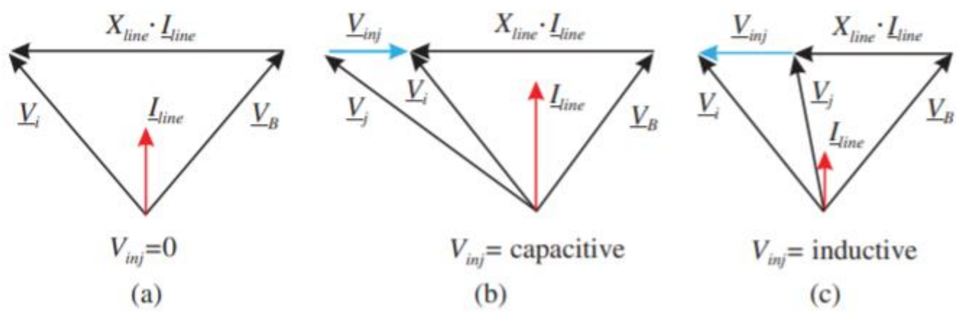


Figure 2.6. SSSC injected voltage (Eremia, et al., 2016)

The phase shift between the line current and the generated voltage of the SSSC by 90° provides almost zero power exchange between the series connected device and the receiving

AC system, except for losses in the converter. This power consumption creates a 1° deviation from the ideal 90°. Thus, there is no need in external power source to charge the DC capacitor. The amplitude of the converter voltage is controlled by the value of the DC voltage. The DC side regulates the output parameter by discharging or charging of the capacitor. The voltage amplitude can also be controlled by PWM (section 2.2). (Eremia, et al., 2016)

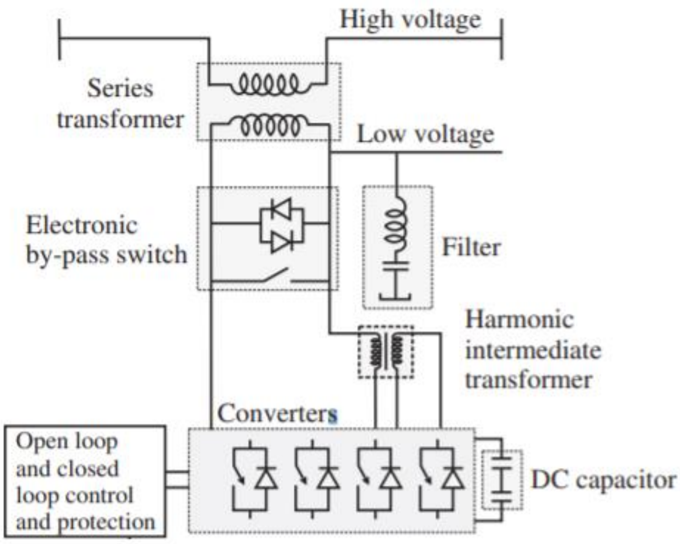


Figure 2. 7 Connection scheme and components of a SSSC (Eremia, et al., 2016)

The SSSC connection scheme is shown in Figure 2. 7. The SSSC consists of five main components (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016):

1. Voltage source converter. The VSC consists of blocks of semiconductor switches, DC capacitor, harmonic filter.
2. Serial transformer (connects the SSSC to the power line).
3. Bypass switch
4. The power source ensures voltage along the capacitor and compensates for losses of the device.
5. Control block

In addition, the SSSC provides fast control and has no negative characteristics of passive devices such as subsynchronous resonance.

2.4.SSSC control

An important question about the SSSC device is the method of regulating the inserted voltage in the line. The value of the injected voltage affects the value of equivalent impedance, current, and power flowing in the line. Therefore, there are several different control methods (Smart Wires, 2020) (ALVIRA, et al., 2010):

1. Insertion of constant value of voltage. The value of the injected voltage does not change and can be either inductive or capacitive. Current and impedance vary depending on the mode.
2. The value of added reactance (capacitive or inductive) is kept constant. The value of the input voltage is changed to keep the reactance value constant.
3. Current control. The amplitude of the current is maintained at the set values.
4. Setpoint control (reactance, injected voltage, or level of the operating current). The controller allows switching to a known operating state rather than adjusting different operating levels during operation.

There are several technical means to control the SSSC device. One of the simplest and most practical methods is the PI controller (Padiyar, 2007). However, other control methods, such as sliding mode control, come into use (Bi, et al., 2016).

A control algorithm determines the active losses in the device, harmonic content, and response time. The major percentage of the losses are in the valve part of the converter, where switching losses are responsible for 50 %. Though, the high switching frequency allows to decrease the harmonic content.

The response time of the converter determines the time to respond to external disturbances in the network. There are two algorithms to control the converter. In static operation modes, the optimum control algorithm is the optimal PWM (OPWM) (Ran, et al., Jan.2002), which allows to suppress low frequency harmonics in voltage curve with the smallest number of switching operations. However, this control algorithm is characterized by the low response time. Concurrently, current following PWM has fast response time and higher switching time characteristics, which leads to additional losses. In this regard, a “polyalgorithm PWM” was proposed in (Peshkov , 2005), when the current following algorithm is used only at modes where fast response to disturbances is required. The rest of the time the control is carried out by the OPWM. (Peshkov., 2008 in Russian)

2.5.SSSC with series transformer

Figure 2.8 shows the SSSC circuit with the series transformer. When S_2 and S_m are open, the secondary winding of the transformer is not short-circuited, and the voltage of the required frequency and amplitude can be injected into the line. When the transformer secondary winding is short-circuited (S_2 and S_m are closed), no additional voltage is generated into the line. However, a small leakage reactance of the serial transformer is added to the line reactive resistance. (EnerNex, 7 February 2018)

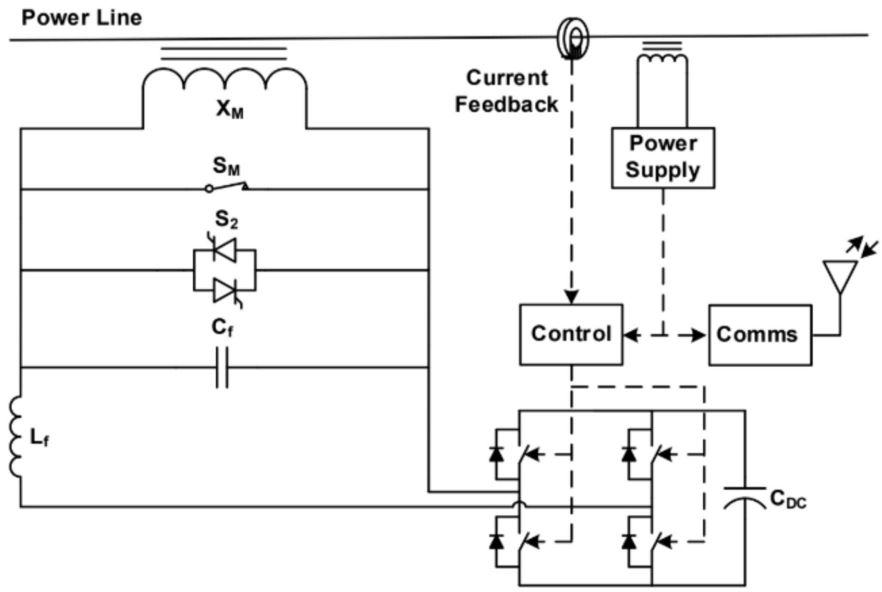


Figure 2.8. Scheme of SSSC with series transformer

2.6.Transformerless SSSC

Developments in power converter technology led to the appearance of 4.5 kV IGBT transistors (Matsumoto, et al., n.d.). In addition, the simple and reliable scheme for balancing series connected IGBTs was invented (Sasagawa, et al., Jul./Aug. 2004). All this, in turn, resulted in very powerful and high frequency multi-level inverters. The use of these technologies in the second generation of IGBTs has made it possible to create transformerless synchronous static compensators (Smart Wires, 2020) (Abbasi & Tousi, 6-9 June, 2017.) (Akagi, et al., 2008).

The transformerless design of the FACTS devices has the following advantages over conventional models (Abbasi & Tousi, 6-9 June, 2017.) (Akagi, et al., 2008) (Stemmler & Beer, 1997) (Peng, et al., 2014):

- elimination of bulky, heavy, and expensive system component (transformer),
- high efficiency,
- fast response to disturbances.

The use of these devices in the electrical system allows to increase its controllability and stability.

2.7. SSSC device in SmartValve complement

SmartValve is the SmartWires modular version of SSSC (Smart Wires, 2020). This facility is a synchronous voltage source based on VSCs. The H-bridge circuit (2.2) of each inverter consists of IGBT transistors (section 2.1.1). The H-bridge converter is controlled in such a way that the voltage is injected directly into the line, i.e. the SmartValve is a direct in-line device, a serial transformer is not required. SSSC is controlled by a current transformer that measures the current in the line. The value of generated voltage is determined by the control method and data obtained from sensing transformer. The SSSC scheme in the SmartValve configuration is shown in Figure 2. 9.

The SSSC power electronic converters are protected by a bypass, the main components of which are normally closed mechanical contactor (VSL), silicon-controlled rectifiers (SCR), metal oxide varistor (MOV) and a differential-mode choke (DMC). Mechanical contactors provide bypassing of the converter. The SCR conducts line currents in the event of malfunctions or during switching of mechanical contactors to turn on or off the compensation device (Smart Wires Reimagine the grid, 2019). The MOV protects internal components from line voltage spikes, such as during lightning impulses and switching loads. A differential-mode choke serves to suppress electromagnetic and radio frequency interference. (Smart Wires, 2020)

The bypass also ensures control functions by providing facilities to bypass the converter during faults conditions. The VSL can be closed and opened by operator according to the system requirements.

SmartValve device operates on line potential and has no grounding. The equipment is installed in all three phases, with the number of installations per phase determined by the required degree of compensation (Smart Wires, 2020).

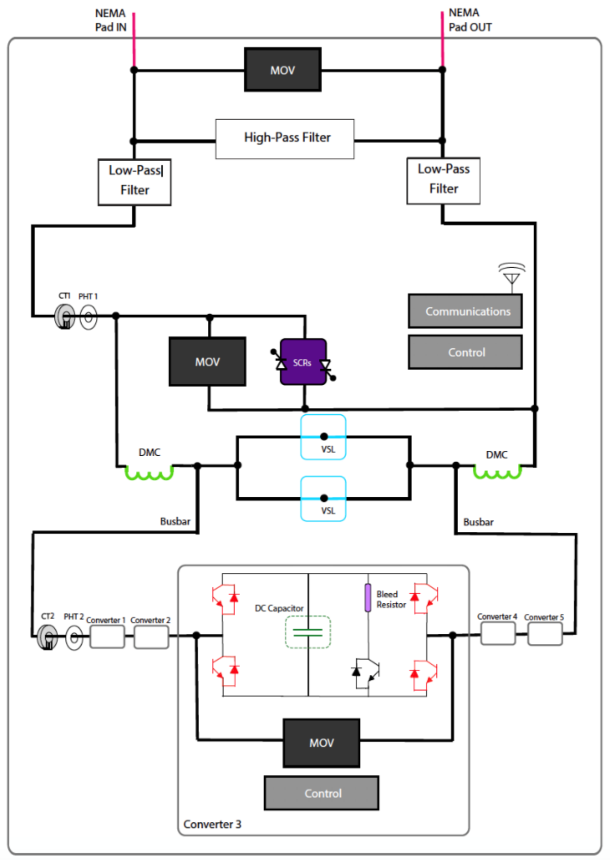


Figure 2. 9. SSSC in SmartValve complete

2.8.Series connected compensating devices

Series connected compensating devices are used in EPS to compensate the line reactance, therefore, to increase the transmission limit of a power line. Those technologies also allow to improve voltage quality, to optimize power flow between parallel lines, to reduce losses, and to improve EPS stability. There are following series connected compensating facilities: (Eremia, et al., 2016)

- Thyristor-Switched Series Capacitor (TSSC),
- Thyristor-Controlled Series Capacitor (TCSC),
- GTO Thyristor-Controlled Series Capacitor (GCSC).

2.8.1. Thyristor-Switched Series Capacitor

TSSC is a string of capacitors connected in series with the power line. Every capacitor is shunted by a bypass valve consisting of thyristors connected in anti-parallel. Thyristors can be only in two states: on or off. When switches are in the non-conductive state, the capacitor compensates the line reactance. In the on state, thyristors are used to bypass the capacitor - no compensation takes place. The compensation ratio is changed by changing the number of capacitors installed in series. The circuit diagram of the TSSC is shown in Figure 2.10. Since bypass valves can only be switched to a non-conductive state when the current is zero-crossing, the capacitor can be switched on just at that point. (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016) (Padiyar, 2007).

The drawback of TSSC is that the full line current flows through thyristors and the risk of subsynchronous resonance. (Padiyar, 2007) (Belyaev, et al., 2017). However, this device will be the least expensive option.

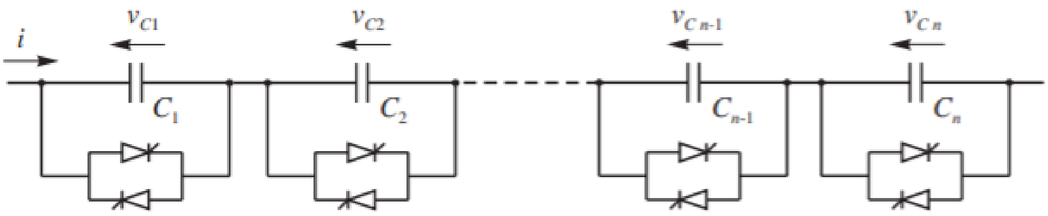


Figure 2.10. Scheme of TSSC (Eremia, et al., 2016)

2.8.2. Thyristor-Controlled Series Capacitor

TCCS consists of a series-connected capacitor shunted by thyristor-controlled reactor (TCR) – Figure 2.11. The TCR provides constant control of serial capacitive compensation. The practical implementation of the TCSC is the serial connection of several of these modules to achieve the required rated voltage and operating characteristics. (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016)

TCSC can operate in three different modes (Eremia, et al., 2016) (Padiyar, 2007):

1. The capacitor is bypassed. The thyristor valve is always open, the current through inductance is continuous and sinusoidal. This mode is used for the capacitor overvoltage

protection. The reactance of the TCSC will be inductive since the capacitive susceptance is lower than inductive.

2. The thyristor valve is blocked – not conducting the current. The full line current flows through the capacitance. This mode is similar to the TSSC operation principal.
3. The thyristor is in partial conductivity mode. This mode allows adjusting smoothly the reactance of the TCSC (inductive or capacitive). However, the direct transition between modes is prohibited since there is a resonance zone between inductive and capacitive mode. The area of inductive conductivity corresponds to an ignition angle from zero to $\alpha_{limit.L}$, and the area of capacitive conductivity corresponds to $\alpha_{limit.C} \leq \alpha \leq 90°$

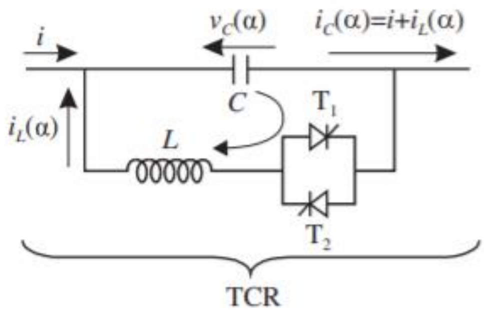


Figure 2.11. Scheme of TCSC (Eremia, et al., 2016)

The advantages of this device are that the TCSC improves the damping properties of the system and is able to eliminate the problem of subsynchronous resonance (Zhang, et al., 2012). It is also capable of switching to an inductive state during short circuits (SC) time, thereby reducing the SC current. Disadvantages include long response time, compensation in discrete domain, and transient process after switching (Eremia & Shahidehpou, 2013).

2.8.3. GTO Thyristor-Controlled Series Capacitor

The GCSC consists of a constant capacitance and a set of GTO thyristors connected in anti-parallel (Figure 2.12). The capacitor voltage is regulated by the ignition angle of the thyristors. GTO provides the ability to switch on and off on command. When thyristors are closed, the current is compelled to flow through the capacitor, thus compensating for the inductive voltage drop in the line. When thyristors are in the open state, no compensation is provided. (Hingorani & Gyugyi , 2000) (Eremia, et al., 2016) (Padiyar, 2007)

The demerits of GCSC before TCSC are the high cost of GTO thyristors and the increased voltage at the TCSC capacitor (Padiyar, 2007). The benefits of GCSC include the reduction of negative effects of subsynchronous resonance (Jesus, et al., 2007). The GCSC will be a good choice in situations where inductive compensation is not required.

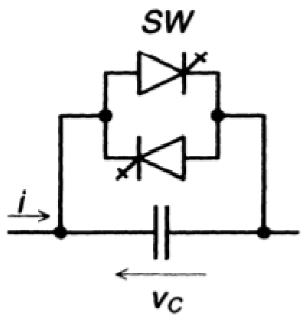


Figure 2.12. Scheme of the GCSC (Eremia, et al., 2016)

2.8.4. The comparison of series connected compensating devices

Table 2.1. The comparison of series connected compensating devices

Criteria	TSSC	TCSC	GCSC	SSSC
Dependence of generated voltage from the value of line current – Figure 2.13	yes	yes	yes	no
Ability to generate active and reactive power to maintain effective X/R ratio	no	no	no	yes
Subsynchronous resonance risk	yes	no	no	no
Oscillation damping	no	yes	yes	yes
Ease of installation of the required protection functions	yes	yes	yes	no

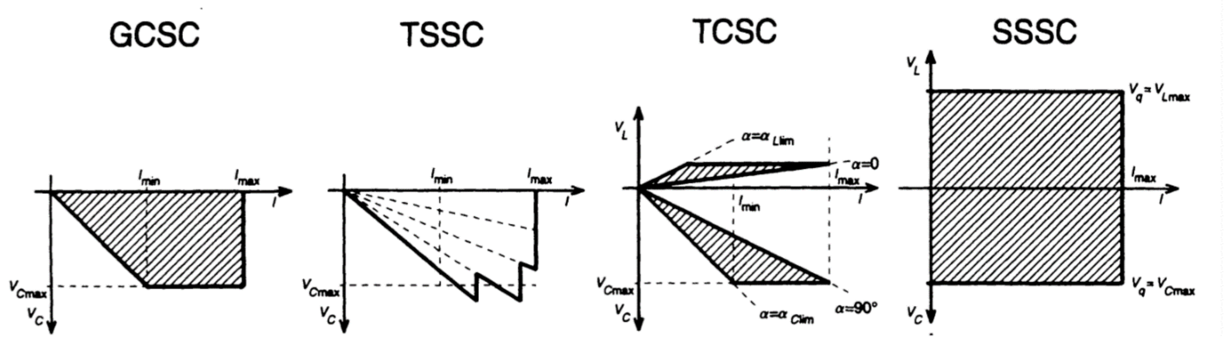


Figure 2.13. Current-voltage characteristics of series connected compensating devices

Improvement of oscillation damping by means of the SSSC occurs due to the fact that the compensator simulates a serial reactance to reduce or increase the line transmitted power, while simultaneously introducing a virtual variable impedance to absorb or supply the active power in accordance with the dominant machine oscillations. While GCSC, TSSC, and TCSC compensators can dampen oscillations only by changing the reactance, thus affecting the power transmission. (Hingorani & Gyugyi , 2000)

Losses in compensation mode will depend on the losses in valves (section 2.1) and in inductive elements. In non-compensation mode, losses will be minimal as current will only flow through the capacitor (Hingorani & Gyugyi , 2000). It should be noted that the SSSC is an expensive device.

2.9.Chapter summary

The overview of the main components, different installation modules, and control of the SSSC is provided. In addition, a comparison between series connected compensating devices is made. The SSSC has several advantages: independence of the generated voltage from the line current, oscillation damping, ability to generate active power flow, and elimination of subsynchronous resonance risk.

2.10. Master thesis goals

The SSSC is capable to actively control operating modes of the EPS, specifically influence the transmission line capacity, transient stability, and power quality. Taking into account the development and growth of the SSSC device application, the relevant agenda is the elaboration of methods for evaluating the efficiency of this technology. As a consequence, the following goals are put within the limits of the given master's thesis work:

1. The development of a mathematical model of SSSC to study the device influence on static and transient stability.
2. Research of the SSSC influence on the operation mode of a single transmission line.
3. Study of the effect of the SSSC on transient processes.
4. Estimation of the SSSC stabilization channels efficiency and optimization of the equipment setup parameters.

Chapter 3

Mathematical model of the calculation scheme

The scheme "generator – transformer – transmission line – infinite bus (IB)" is taken as a calculation scheme and is shown in Figure 3. 1. The SSSC device connected in the middle of the line.

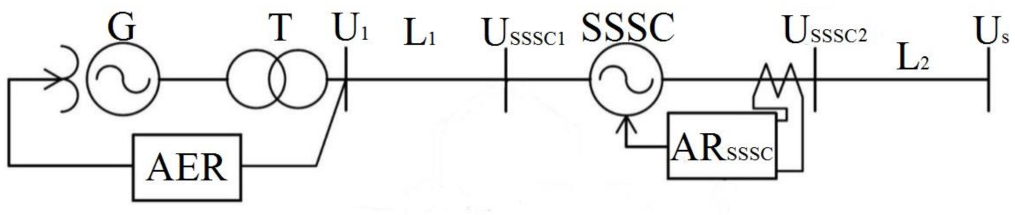


Figure 3. 1 Calculation scheme

3.1.Generator mathematical model

One of the main objectives in the system modeling, shown in Figure 3. 1, is mathematical simulation of a synchronous machine (SM) with automatic excitation regulator (AER). In the framework of this research it is sufficient to simulate a SM with one equivalent circuit for each phase winding, one equivalent circuit for the field winding and equivalent amortisseur winding in direct and quadrature axes. The transients of a SM are described using the Park-Goreva equation system with the assumptions described in (Belyaev , et al., 2012).

The SM equations are written in per unit (p.u.) values, which simplifies numerical analysis and makes recording of the equations more visual (Belyaev , et al., 2012). In the mutual p.u. system differential equations of the transient process describe as follows:

$$\frac{1}{\omega_c}\frac{d\psi_d}{dt} + (1+s)\cdot\psi_q + r\cdot i_d = -u_d$$

$$(1+s)\cdot\psi_d - \frac{1}{\omega_c}\frac{d\psi_q}{dt} - r\cdot i_q = u_q \tag{2.1}$$

$$\frac{1}{\omega_c}\frac{d\psi_r}{dt} + r_r\cdot i_r = u_f$$

$$\frac{1}{\omega_c}\frac{d\psi_{rd}}{dt} + r_{rd}\cdot i_{rd} = 0 \tag{2.2}$$

$$\frac{1}{\omega_c}\frac{d\psi_{rq}}{dt} + r_{rq}\cdot i_{rq} = 0$$

$$T_J\frac{ds}{dt} = M_t - M_e$$

$$M_e = i_q\cdot\psi_d - i_d\cdot\psi_q \tag{2.3}$$

$$\frac{d\delta}{dt} = \omega_c\cdot s$$

Where ψ_d, ψ_q are direct-axis and quadrature-axis stator flux linkage,

ψ_r is field flux linkage,

ψ_{rd}, ψ_{rq} are direct-axis and quadrature-axis amortisseur flux linkage,

u_d, u_q are direct-axis and quadrature-axis stator terminal voltage,

u_f is field voltage,

i_d, i_q are direct-axis and quadrature-axis stator current,

i_r is field current,

i_{rd}, i_{rq} are direct-axis and quadrature-axis amortisseur current,

r is stator resistance,

r_r is field resistance,

r_{rd}, r_{rq} are direct-axis and quadrature-axis amortisseur resistance,

ω_c is synchronous frequency

T_J is mechanical inertia constant,

M_t is torque moment

M_e is electromagnetic moment

δ is angle between rotor quadratic axis and stator voltage

s is rotor slip.

The power of the primary motor determines the mechanical torque on the machine shaft, which is kept constant in this work. However, in the power system there is a continuous change of load, so modern generators are equipped with an automatic speed regulator (ASR), which regulates the flow of energy, thereby increasing or decreasing the speed of the turbine.

One of the assumptions (Belyaev , et al., 2012) is the existence of a unified magnetic flux (There is a single mutual flux linkage of a SM and independent of it and of each other leakage fluxes) . Then flux linkage expressions are:

$$\psi_d = x_d i_d + x_{ad} i_r + x_{ad} \cdot i_{rd} \qquad where\ x_d = x_{ad} + x_s$$
$$\psi_q = x_q i_q + x_{aq} \cdot i_{rq} \qquad where\ x_q = x_{aq} + x_s \tag{2.4}$$

where x_d, x_q are direct-axis and quadrature-axis synchronous reactance,

x_{ad}, x_{aq} are direct-axis and quadrature-axis mutual reactance (between stator and rotor),

x_s is stator leakage reactance.

For the connection of the rotor and stator circuits, auxiliary variables are introduced: ψ_{ad} and ψ_{aq}, which describes the mutual flux linkage of the rotor and stator circuits in the direct and quadrature axes. And can be expressed as:

$$\psi_{ad} = \psi_d - x_s \cdot i_d$$
$$\psi_{aq} = \psi_q - x_s \cdot i_q \tag{2.5}$$

Then the flux linkage of rotor windings:

$$\psi_r = \psi_{ad} + x_{sr} \cdot i_r$$
$$\psi_{rd} = \psi_{ad} + x_{srd} \cdot i_{rd} \qquad (2.6)$$
$$\psi_{rq} = \psi_{aq} + x_{srq} \cdot i_{rq}$$

Where x_{sr}, x_{srd} and x_{srq} are field leakage reactance, direct-axis and quadrature-axis amortisseur leakage reactance respectively.

The equations of stator circuits can also be written via subtransient electromotive forces:

$$x''_q i_q - E''_d = -u_d$$
$$x''_d i_d - E''_q = u_q$$
$$E''_q = \frac{\frac{1}{x_{sr}}\psi_r + \frac{1}{x_{srd}}\psi_{rd}}{\frac{1}{x_{ad}} + \frac{1}{x_{sr}} + \frac{1}{x_{srd}}};\ E''_d = \frac{\frac{1}{x_{srq}}\psi_{rq}}{\frac{1}{x_{aq}} + \frac{1}{x_{srq}}} \qquad (2.7)$$
$$x''_d = x_s + \frac{1}{\frac{1}{x_{ad}} + \frac{1}{x_{sr}} + \frac{1}{x_{srd}}};\ x''_q = x_s + \frac{1}{\frac{1}{x_{aq}} + \frac{1}{x_{srq}}}$$

Where

$$\psi_d = u_q\ , \psi_q = -u_d \qquad (2.8)$$

The equations of SM in the steady-state mode can be obtained from *(2.1)* by excluding derivatives and equating s=0. Omitting intermediate transformations, the system of equations is following:

$$E_Q = \sqrt{\left(U + \frac{P \cdot r + Q \cdot x_q}{U}\right)^2 + \left(\frac{P \cdot x_q - Q \cdot r}{U}\right)^2}$$

$$E_q = E_Q - (x_d - x_q) I_d$$

$$\delta = arctg \frac{\frac{P \cdot x_q - Q \cdot r}{U}}{U + \frac{P \cdot r + Q \cdot x_q}{U}} \qquad (2.9)$$

$$U_q = U \cdot \cos(\delta), \qquad U_d = -U \cdot \sin(\delta)$$

$$I_d = \frac{(U_q - E_Q) \cdot x_q - r \cdot U_d}{{x_q}^2 + r^2}, I_q = \frac{-U_d - r \cdot I_d}{x_q}$$

Where E_q is quadrature-axis synchronous stator electromotive force and in p.u. values equal to $x_{ad} i_r$.

E_Q is auxiliary stator electromotive force when $x_d \neq x_q$.

In order to increase the stability of synchronous generators in case of disturbances, the system uses AER. The most known regulator type in Russia is the AER of strong action. Its main functionality are (Belyaev , et al., 2012) (Yurganov & Kozhevnikov, 1996)

- stabilization of the output parameters of SM, namely, maintenance of a given value of voltage and attenuation of small and large oscillations occurring in the power system,
- excitation boost to ensure a high level of transient stability,
- stable regulation in all modes of operation of the generator.

A simplified scheme of the AER of strong action is shown in Figure 3.2. The voltage block consists of channels expressed by voltage deviation and by voltage derivative. The derivative component reacts to voltage changes and predicts the magnitude and direction of the error. The regulation droop is inversely proportional to K_{0u}.

A frequency block consists of frequency deviation and frequency derivative channels. These control channels are responsible for stabilizing the external angle of the system. The transfer function $W_{fb} = \frac{p}{T_{fb}p+1}$ converts the signal Δδ into $\Delta\omega_0$. The control channel of the derivative of the current field winding provides stabilization of the internal SM angle.

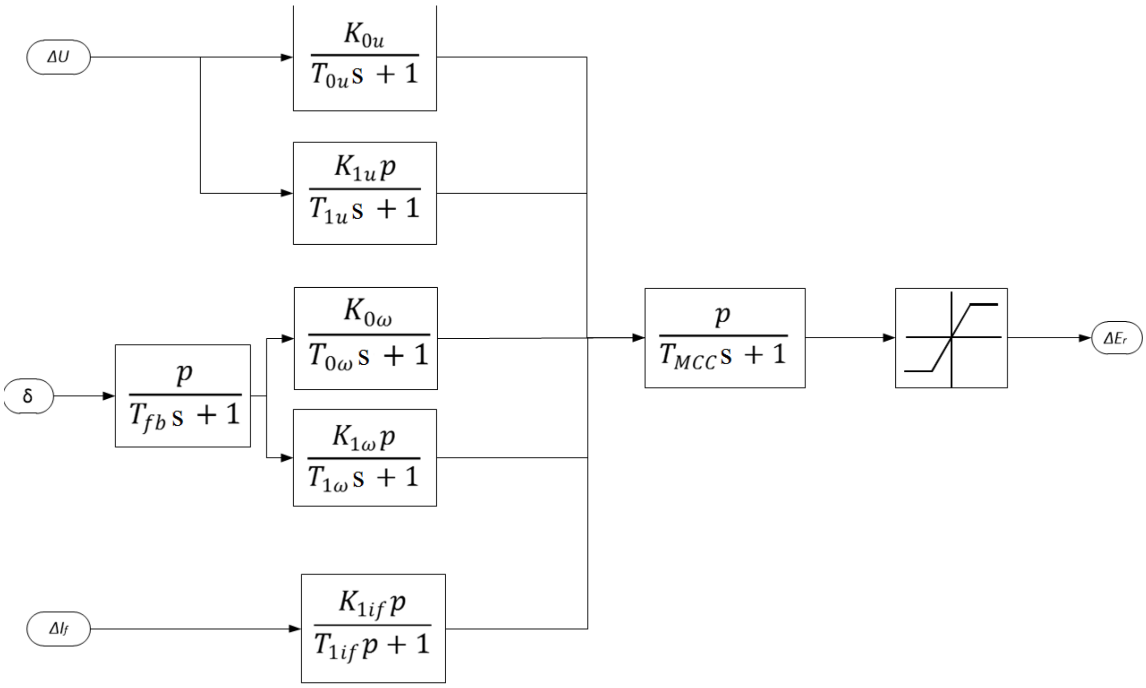


Figure 3.2. A simplified scheme of the automatic excitation regulator of strong action

The summation of all control and stabilization signals comes to the main control channel (MCC). The output signal of MCC is the regulator output signal. Also, the output signal limiter should be taken into consideration, which functions according to:

$$E_r = \begin{cases} E_{rmax}, & E_r > E_{rmax} \\ E_r, E_{rmin} < E_r < E_{rmax} \\ E_{rmin}, & E_r < E_{rmin} \end{cases} \tag{2.10}$$

E_{rmax} – excitation voltage during boost;

E_{rmin} – excitation voltage during de-excitation.

3.2.SSSC mathematical model

The mathematical model of the SSSC device for the electromechanical transient processes calculation is described by the algebra-differential system of equations. The facility regulates only the reactive power of the system, where the control effect is a change in the current setpoint. (Eremia, et al., 2016) (Padiyar, 2007) (Belyaev , et al., 2012) (Kochkin & Shakaryan, 2011)

The value of the current flowing in the line at the SSSC point of connection is the input variable of the regulator. The equations are written down in q,d coordinate system, because mathematical model of SSSC is connected with mathematical model of generator. Therefore, the current value is represented by components on the axis d and q - I_q and I_d. The rated power of the SSSC is specified in the input data.

The current control signal is calculated using the following transfer function:

$$\Delta I_m = \frac{K_{0i} \cdot (I_m - I_{set})}{1 + pT_i} \qquad (2.10)$$

Where I_{set} is the current setpoint value,

K_{0i} is current proportional gain,

T_i is time constant of current deviation channel (T_i = 0,01 c);

The SSSC electromagnetic force (emf) components in the direct and quadrature axes are computed with the use of transfer functions with consideration of additional control signals by rotor generator slip deviation in relation to the synchronous axis or control signal by the voltage frequency deviation at the point of connection:

$$\Delta U_q = \frac{S_{SSSC} \cdot \Delta I_m \cdot I_d}{1 + pT_{SSSC}}; \qquad (2.11)$$

$$\Delta U_d = -\frac{S_{SSSC} \cdot \Delta I_m \cdot I_q}{1 + pT_{SSSC}};$$

Those control methods implement current regulation. Where S_{SSSC} is facility rated power,

I_d, I_q are SSSC current components,

T_{SSSC} is time constant of SSSC converter.

The SSSC emf components with the additional slip signal:

$$\Delta E_q = \Delta U_q + \frac{K_{0f} \cdot f}{1 + pT_{0f}} + \frac{K_{1f} p \cdot f}{1 + pT_{1f}};$$

$$\Delta E_d = \Delta U_d + \frac{K_{0f} \cdot f}{1 + pT_{0f}} + \frac{K_{1f} p \cdot f}{1 + pT_{1f}}; \qquad (2.12)$$

The SSSC emf components with the additional frequency signal:

$$\Delta E_q = \Delta U_q + \frac{K_{0f} \cdot f}{1 + pT_{0f}} + \frac{K_{1f} p \cdot f}{1 + pT_{1f}};$$

$$\Delta E_d = \Delta U_d + \frac{K_{0f} \cdot f}{1 + pT_{0f}} + \frac{K_{1f} p \cdot f}{1 + pT_{1f}}; \qquad (2.13)$$

Where T_{0s}, T_{0f} are time constant of slip and frequency deviation channels ($T_{0s} = 0{,}01$ c, $T_{0f} = 0{,}02$ c),

T_{1s}, T_{1f} are time constant of slip and frequency derivative channels ($T_{1s} = 0{,}01$ c, $T_{1f} = 0{,}02$ c),

K_{0s}, K_{0f} are slip and frequency proportional gains,

K_{1s}, K_{1f} are slip and frequency derivative gains.

The slip deviation channel and its derivative are theoretical and are used to reflect potential capabilities. In the power system, the main control channel is the frequency deviation and derivative at the SSSC connection point.

The emf value is limited in such a way that the power generated by the SSSC cannot exceed the rated power of the device.

3.3.Chapter summary

In the conditions of a single power transmission line the method of mathematical modeling of the FACTS device is developed, based on the representation of SSSC by adjustable emf source. The introduced stabilization channels of the facility are able to influence the oscillation damping in the power system at disturbances, as well as transient processes. In addition, the model allows to study the impact of the SSSC on steady-state mode.

Chapter 4

SSSC as a method to improve transmission line controllability and transient stability

The characteristic property of the SSSC device is the transformation of the EPS elements from “passive” means of electric power transport into “active” mode control units. These technologies are capable of fast-changing power transmission characteristics to ensure optimal network operation based on the following criteria: increasing capacity, increasing stability, and real power flow rescheduling. Thus, the application of these technologies opens up new means of solving the problems of energy system management and stability.

The method of impact on transmission line limit (transfer capacity maximum value) is described using the following equation:

$$P_m = \frac{|\dot{U}_1| \cdot |\dot{U}_2|}{Z_c \cdot \sin\ \alpha_0 l} \cdot \sin\ \delta \qquad (2.14)$$

Where Z_c – line characteristic impedance, $\alpha_0 l$ – line wave distance.

Taking into account that the characteristic impedance and wave distance of a line are invariable, and SSSC is a series regulating device, then under control actions the value of the shift angle between voltages in the beginning and the end of a transmission line is changed. Increasing the transmission line capacity limit of existing lines allow to avoid new network construction for power transfer from redundant to deficit power systems, as well as to expand the output of active power from power plants by increasing the maximum admissible power flow up to the thermal resistance limits. (The standard of organization., 2009)

In addition, the angle value variation facilitates the redistribution of power flows between parallel lines, enabling to reduce the transmission lines losses and to load transmission line optimally maximizing carrying capacitance.

Enhancing system stability reduces the risk of falling out of the system synchronous operation, thus excluding, or replenishing the impact of emergency automatics, which prevents these disturbances. A reduced number of control actions from emergency automatics contributes to the decreased amount of load and generator outages. This in turns leads to (The standard of organization., 2009):

- A shortage of emergency reserve in power system,
- Lowering losses from electrical energy underproduction at power plants,
- Reduction of compensation payments to consumers in the event of power supply interruptions,
- Saving of fuel needed to restart a generating unit.

4.1.Description of the simulated scheme

The simulated circuit is a single electricity transmission scheme shown in Figure 3. 1. To describe the generator model, the parameters of TBB -800 (Hydrogen-water-cooled synchronous turboalternator) were used with cosφ=0.9 – **Ошибка! Источник ссылки не найден.**. A transmission line with 500 kV rated voltage and a 450 km length was considered. The described system is close to the transient stability limit at heavy disturbances (three-phase short circuit). Transformer and line parameters are provided in Table 4. 2 and 4.3. The input data of generator is provided in p.u. values, where apparent output power considered as base power:

$S_{base} = 889$ MVA

Table 4. 1. Generator parameters

P_g	Q_g	U	x_d	x_q	x_s	x'_d
0.9	*0.436*	*1.025*	*2.33*	*2.28*	*0.184*	*0.304*
x''_d	x'_q	r_r	r_{rd}	r_{rq}	r	T_J, *c*
0.216	*0.238*	$0.542 \cdot 10^{-3}$	*0.0185*	*0.02*	*0*	*5.3*

Table 4. 2. Transmission line parameters

R_{line}, Ω	X_{line}, Ω	B_{line}, mS
11,25	137,7	1.629

Table 4. 3. Transformer parameters

R_{tr}, Ω	X_{tr}, Ω	ΔQ, kVAr
0,55	40	1.629

4.2. SSSC regulating characteristics

The operation mode of the electric network is characterized by a constant change in load capacity, network topology and generation capacity value, which in turns leads to variances in mode parameters. The SSSC performs active management of the EPS operation modes. Therefore, it is necessary to obtain correlations illustrating the influence of the facility on operation modes of power transmission.

The process of power transmission mode changes under the SSSC actions is illustrated in Figure 4. 1. The device generates only reactive power; consequently, the injected voltage vector is 90° lead or log the line current vector. Thus, it compensates or increases the voltage drop in the line. All calculations are made for the installation capacity amount to 0.2 p.u. with a current control effect of 0.4 p.u. The control gain of the current deviation channel is K_{0i} = -10 units change in output voltage per current deviation unit.

Figure 4. 1 depicts the current setpoint changes in the direction of the line current growth. The generator electromagnetic power (red curve) increases and the generator rotor starts to decelerate according to *(2.3)*, and after oscillatory process, it reaches a new stable point with the decreased angle value δ (blue curve). The value of electromagnetic power does not change after the damping of the oscillations since it is determined by the primary engine power. At change of current setpoint in the direction of the decreased line current, the electromagnetic power surge drops (pink curve) and the angle increases (green).

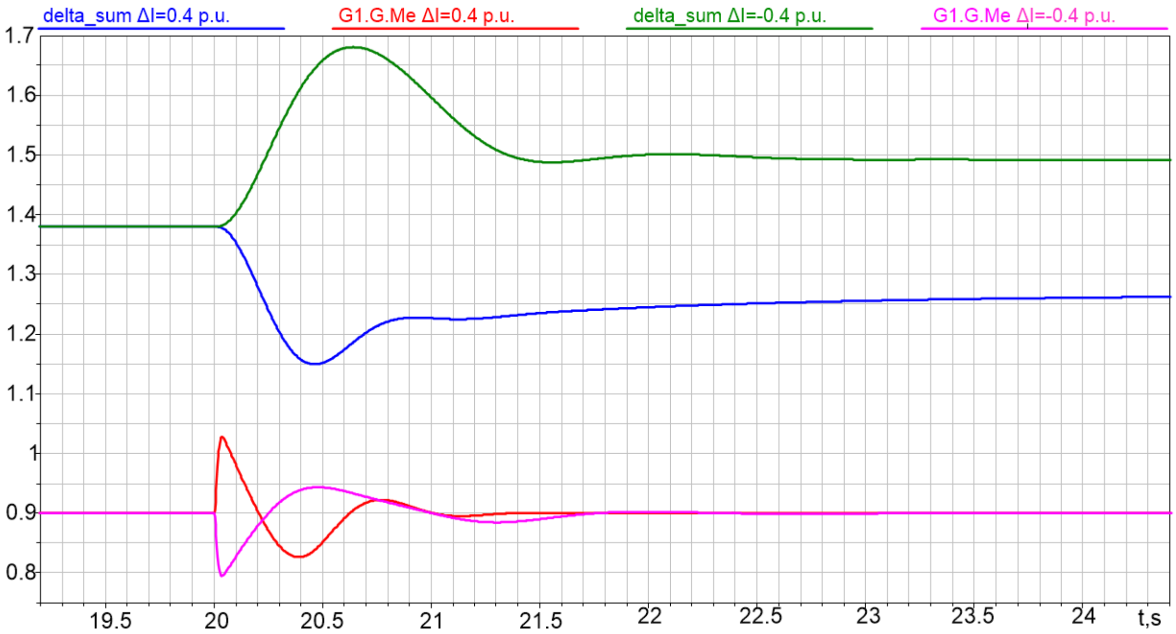


Figure 4. 1. Alternation of the electricity transmission angle (blue and green curve) and electromagnetic power (red and pink curve) with the SSSC current setpoint is changed

Altering the SSSC current control effect leads to the formation of ΔE_{SSSC}, which is in quadrature with the line current. Thus, creating additional or compensating line voltage drop. The occurrence of this additional voltage drop (inductive or capacitive) lead to changes in the transmission power characteristics. When the displaying the current and voltage vector in the d,q coordinate system, the ΔE_{SSSC} is at the third quadrant at positive setpoint and in the first quadrant at negative setpoint. All of this shown in Figure 4. 2 and Figure 4. 3.

Figure 4. 2 depicts changes of the operation mode at set point processing in the direction of the line current growth by 0.4 p.u., where U_s is the voltage vector of the receiving system, U_l is the voltage vector at the beginning of the transmission line, I – current at the SSSC connection point. Variables with one stroke illustrates the value before the change of the setpoint, with two is after. Part of the line voltage drop is compensated by the emf generated by SSSC. This reduces the angle between the generator quadrature axis and the voltage of receiving system. The current similarly shifts toward the quadrature axis.

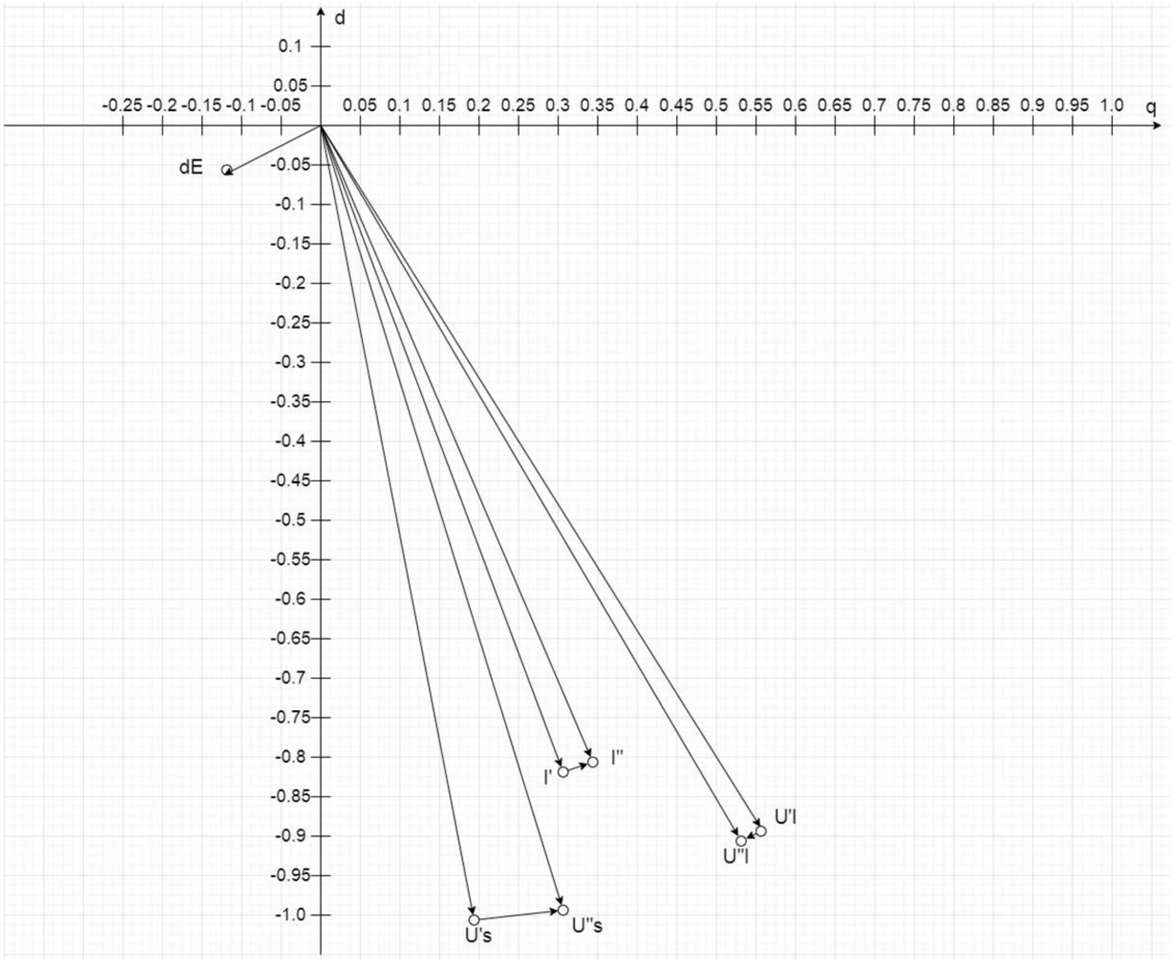


Figure 4. 2. Voltage and current vector diagram when the setpoint is changed upwards by 0.4 p.u

When the setpoint is changed towards the line current drop , an additional voltage drop generated by SSSC is added to the line voltage drop – Figure 4. 3. The angle between voltages of receiving and transmitting systems is increased.

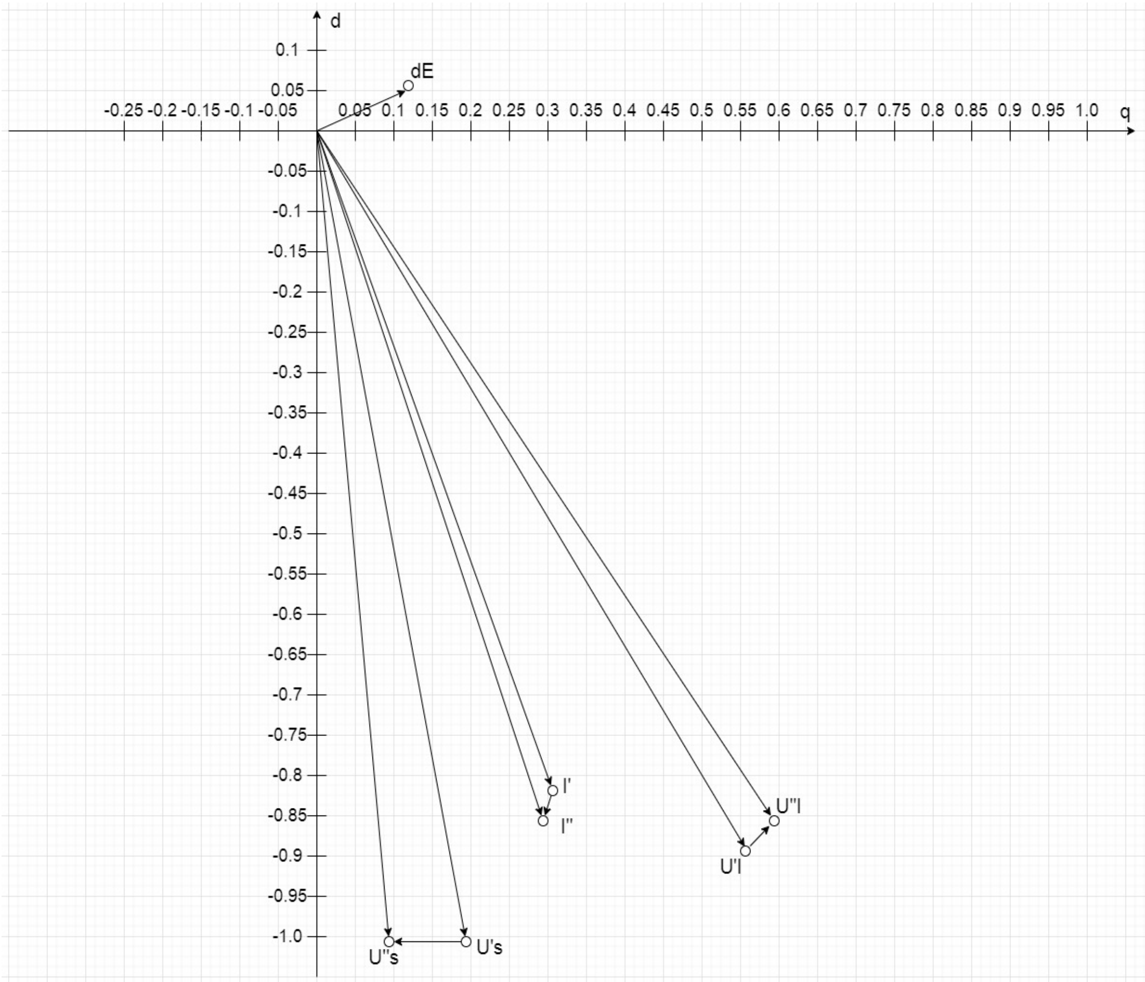


Figure 4. 3. Voltage and current vector diagram when the setpoint is changed downwards by 0.4 p.u

Figure 4.4 depicts the changes in the current flow after the control actions. In case of setpoint for increased current, the generated compensated voltage increased (2.10 and 2.11), and the transmitted power does not change, respectively, the current in the line decreases. At the beginning of the process the incrementation of the current can be observed since the variation of power reactive balance occurred. In the opposite case (additional voltage drop), the current steady state value rises.

When the additional voltage is injected into a line, the equivalent line length virtually declines or inclines. This alters the natural frequency oscillations. With the capacitive compensation the line oscillation frequency increases, while with inductive compensation it decreases.

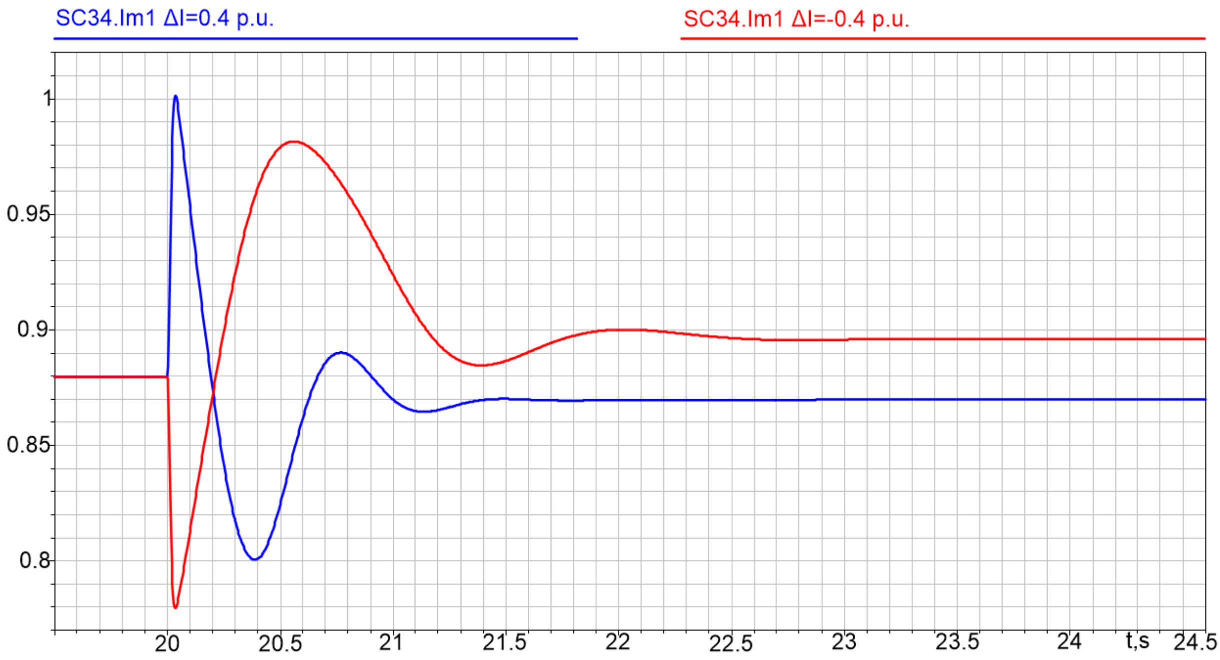


Figure 4.4. Current at the SSSC point of connection

Figure 4. 5 shows the change in voltage at the SSSC terminals from the transmitting side (blue and green curves) and the receiving side (red and pink curves). When the setpoint is set to compensate voltage drop, the value of both voltages increases. However, the voltage at the generator side rises to the lesser extent. When the addition drop is added, the voltage on the IBS side declines to a greater extent.

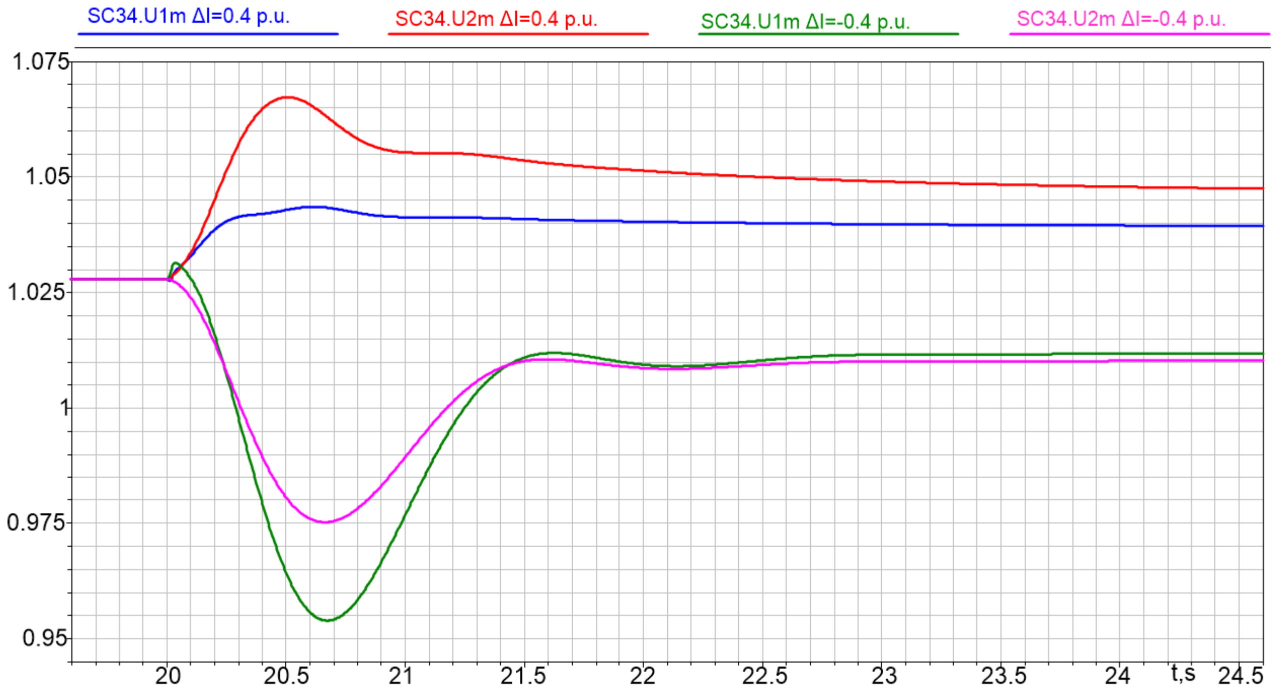


Figure 4. 5. Voltages at SSSC terminals

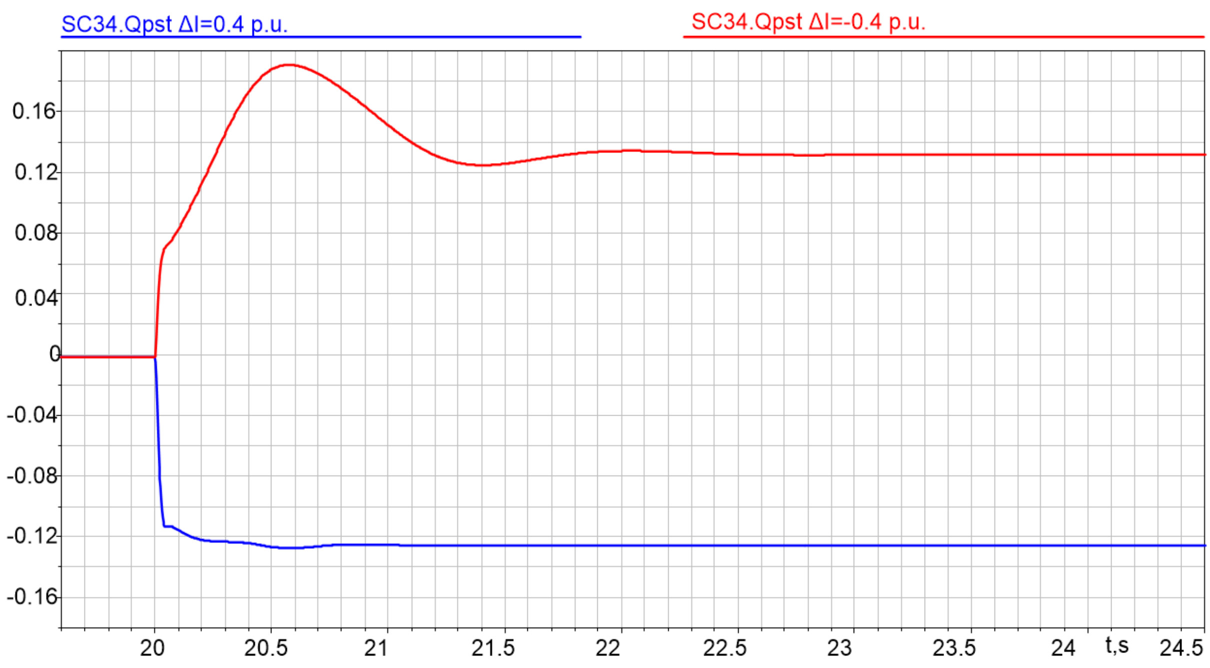


Figure 4. 6. The SSSC generated reactive power

The effect on the operation mode is achieved due to the generation of reactive power only – Figure 4. 6. During compensation mode, the line current decreases due to the increase of the voltage at the SSSC outputs. This results in the increase of the injected reactive power, the value of which will be limited if it exceeds the rated power of the device.

The influence of the SSSC on the regulation can be additionally displayed on the basis of the evaluation of the changes in the transmission angle and line current with the increasing value of device rated power (Figure 4. 7 and Figure 4. 8). The value of transmission angle decreases with the capacitive nature of compensation by 6%. With the inductive nature the angle reduces by 7%. Grey curves show the SSSC's capabilities in terms of current boost or limitations.

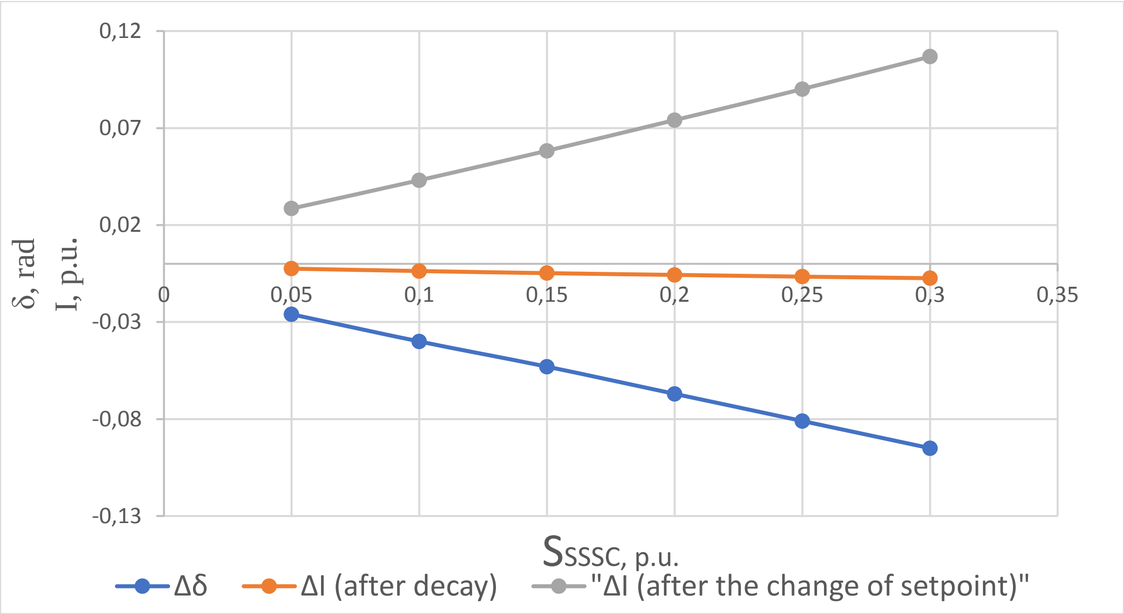


Figure 4. 7. Changes in line current and transmission angle for compensation mode

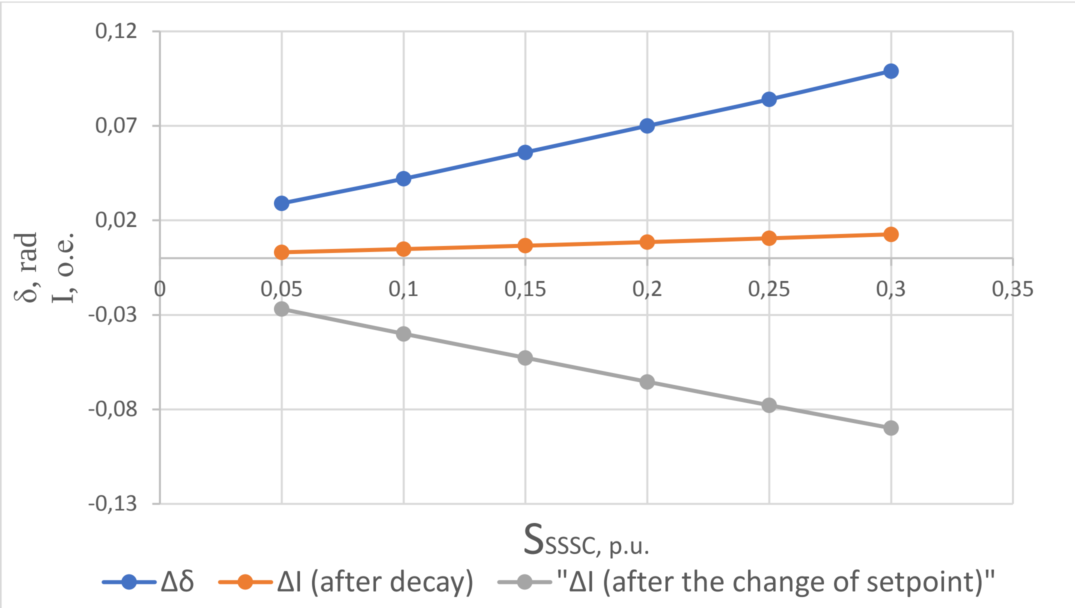


Figure 4. 8. Changes in line current and transmission angle for inductive voltage generation mode

4.3.Transient process at three-phase short circuits

In order to assess the impact of the SSSC device on transient process, it is necessary to initially study the behavior of the system after disturbances without series connected compensating technology. The synchronous generator, which is equipped with AER of strong actions, is responsible for maintaining stability in the system. This type of regulator not only reacts to deviation of controlled parameters, but also to their derivative (section 3.1). This feature allows to detect in advance the history parameter of transients. AER with strong actions provides constant regulation of the excitation voltage with the ability to double boost at the initial stage of the process. The regulator parameters provide in Table 5. 2. The choice of the parameters is explained in chapter 5.

The determination of critical fault clearance time was made on the first angle fluctuation. For the three-phase short-circuit at the beginning of the line, the Δt_{SC} was 0.105 s. This system point was chosen for easy analysis and comparison of the results.

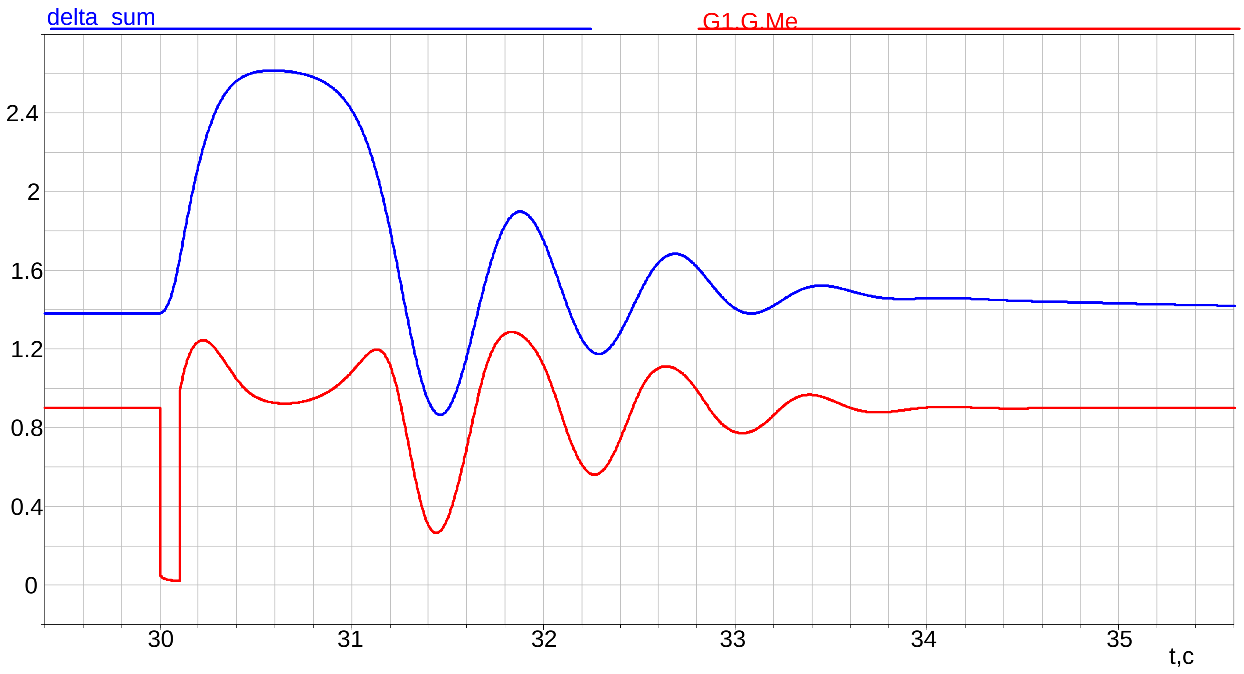


Figure 4. 9. Changes of electromagnetic power (red curve) and full angle (blue) at three phase short circuit at the beginning of the line

The obtained curves of the electromagnetic power and transmission angle depicts at Figure 4. 9. The location of the system near the transient stability boundaries can be represented by the electromagnetic curve whose value almost reaches the value of the mechanical power (0.9 p.u.).

Changes in the voltage at the short circuit point and at the generator terminals is illustrated in Figure 4.10. It can be noted that voltage at the beginning of the transmission line is reduced to zero and on generator terminals to 0.38 p.u.

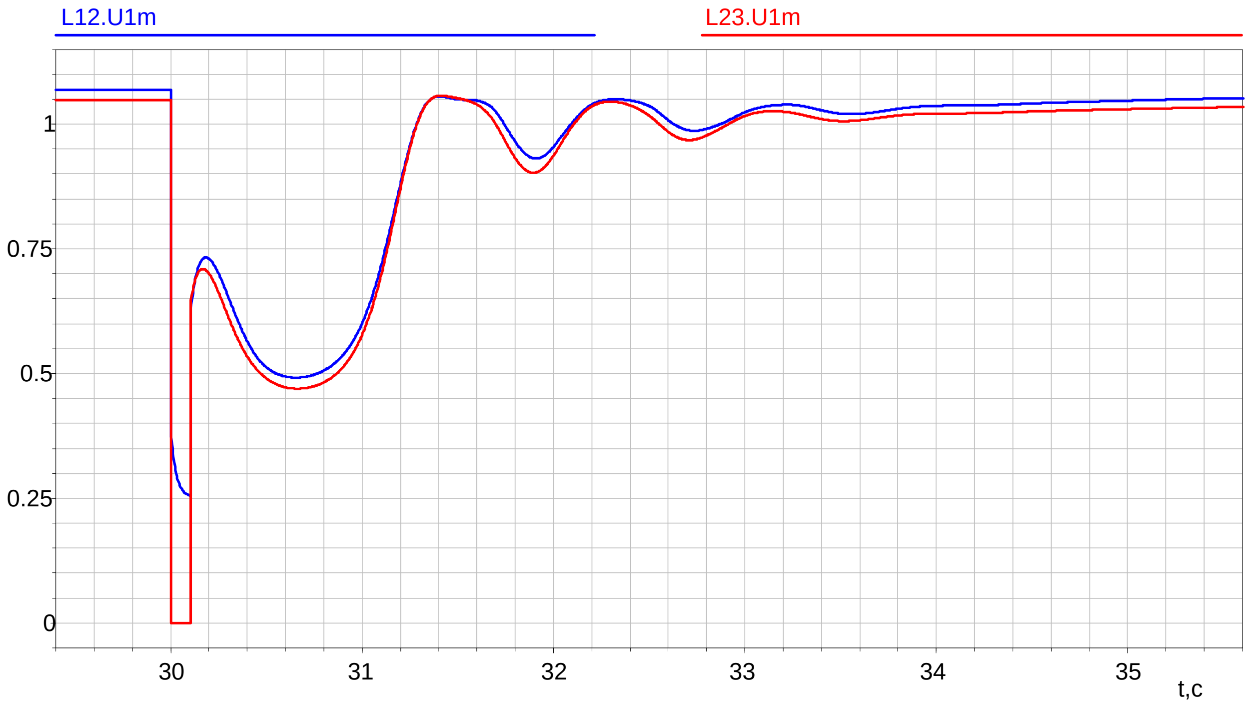


Figure 4.10 Voltage changes at the short circuit point (red curve) and at generator terminals (blue)

4.4.SSSC effect on the critical fault clearance time

The analysis of SSSC effect on the critical fault clearance time was performed for two regulation values for the current deviation channel K_{0i} and for different device rated power values. Two operating modes were considered: inductive reactance compensation mode aimed to stabilize the line current (negative K_{0i}) and opposite of stabilization with positive K_{0i}. The results of the calculation of the critical fault clearance time provided in Table 4. 4.

From the viewpoint of increasing the critical fault clearance time (Δt_{SC}), the deleterious impact of the negative current channel is obvious. With the rise of the rated power the short circuit duration decreases, as the device has greater control effect to limit the line current. With the positive value of K_{0i} Δt_{SC} rises which is due to the fact that generator stator current increases. Respectively, the electromagnetic power increases in the time interval from the short-circuit moment to the first maximum of the angle fluctuations. In this case, an increment in the SSSC rated power has a beneficial effect on the short-circuit duration time since the current value can reach higher value.

Table 4. 4. The value of the critical fault clearance time

SSSC rated power, p.u.	Regulation	Critical fault clearance time, s
Without SSSC		0,105
0.05	K_{0i}=-10	0.101
0.1		0.098
0.15		0.093
0.2		0.088
0.25		0.080
0.3		0.074
0.05	K_{0i}=-20	0.101
0.1		0.098
0.15		0.093
0.2		0.088
0.25		0.080
0.3		0.070
0.05	K_{0i}=10	0.107
0.1		0.110
0.15		0.112
0.2		0.115
0.25		0.117
0.3		0.118
0.05	K_{0i}=20	0.107
0.1		The oscillation instability of the steady-state mode
0.15		
0.2		
0.25		
0.3		

To dampen the oscillations occurring for positive K_{0i}, the channel for rotor slip of voltage frequency deviation (section 3.2). The critical fault clearance time dependences represented in Table 4. 5 - 4.8.

Table 4. 5. Value of the critical fault clearance time with slip and frequency deviation channels

SSSC rated power, p.u.	Regulation	Critical fault clearance time, s
Without SSSC		0,105
0.05	K_{0i}=-20 K_{0s}=-10	0.101
0.1		0.098
0.15		0.093
0.2		0.088
0.25		0.081
0.3		0.075
0.05	K_{0i}=-20 K_{0f}=-0.1	0.101
0.1		0.098
0.15		0.093
0.2		0.088
0.25		0.081
0.3		0.073

Table 4. 6. Value of the critical fault clearance time with slip and frequency deviation channels

SSSC rated power, p.u.	Regulation	Critical fault clearance time, s
Without SSSC		0,105
0.05	K_{0i}=10 K_{0s}=-10	0.107
0.1		0.110
0.15		0.112
0.2		0.115
0.25		0.117
0.3		0.118
0.05	K_{0i}=10 K_{0f}=-0.1	0.107
0.1		0.110
0.15		0.112
0.2		0.115
0.25		0.117
0.3		0.118

The introduction of the additional channel does not significantly affect the critical fault clearance time. Correspondingly, for the current stabilizing SSSC mode addition actions should be taken in case of heavy system disturbances. The series connected device should be switched off or changed to the mode with positive current deviation channel.

The generator rotor slip stabilization channel contributes to maintain oscillatory stability after perturbation at positive K_{0i}. It should be noted that with the coefficient value of the current deviation channel value equals to 20, it is necessary to increase the value of K_{0s} with the rise of SSSC rated power, while the voltage frequency deviation channel does not contribute at all to the oscillation stabilization. More detailed adjustment of stabilization channels will be considered in chapter 5.

Table 4. 7. Value of the critical fault clearance time with slip and frequency deviation channels

SSSC rated power, p.u.	Regulation	Critical fault clearance time, s
Without SSSC		0,105
0.05	K_{0i}=20 K_{0s}=-50	0.107
0.1		0.110
0.15		0.112
0.2		0.115
0.25		0.117
0.3		0.118
0.05	K_{0i}=20 K_{0s}=-10	0.107
0.1		0.110
0.15		0.112
0.2		0.115
0.25		The oscillation instability of the steady-state mode
0.3		

The dependence between the transmission angle increments and the SSSC rated power represented in Figure 4. 11. Angle increments shows the difference between the angle value at first fluctuation without the use of device and with it. As the power of the unit grows, the angle increment increases (at the same perturbation the angle reaches smaller values).

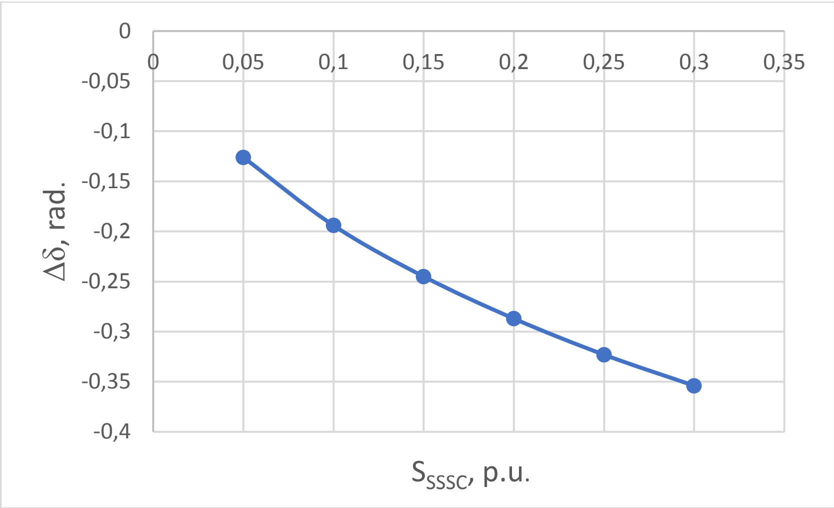


Figure 4. 11. Increase in the power transmission angle on the first fluctuation

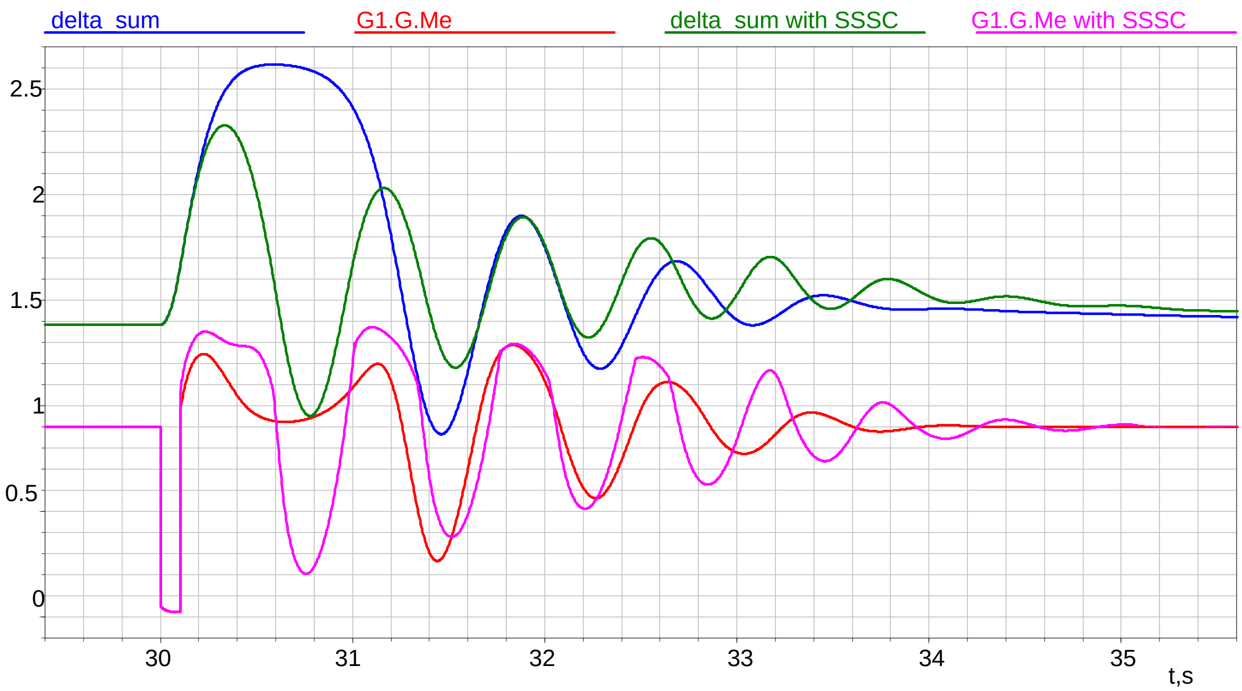


Figure 4. 12. Changes in the transmission angle (blue and green curves) and electromagnetic power (red and pink curves) at short circuit duration 0.105 s

The SSSC efficiency with 0.2 p.u rated power and K_{0i}=10 is confirmed by curves in Figure 4. 12 – 4.14. The key factor of increasing the clearance time is the enlarged value of the generator current after the short circuit clearance. This contributes to the higher value of the electromagnetic power (Figure 4. 14).

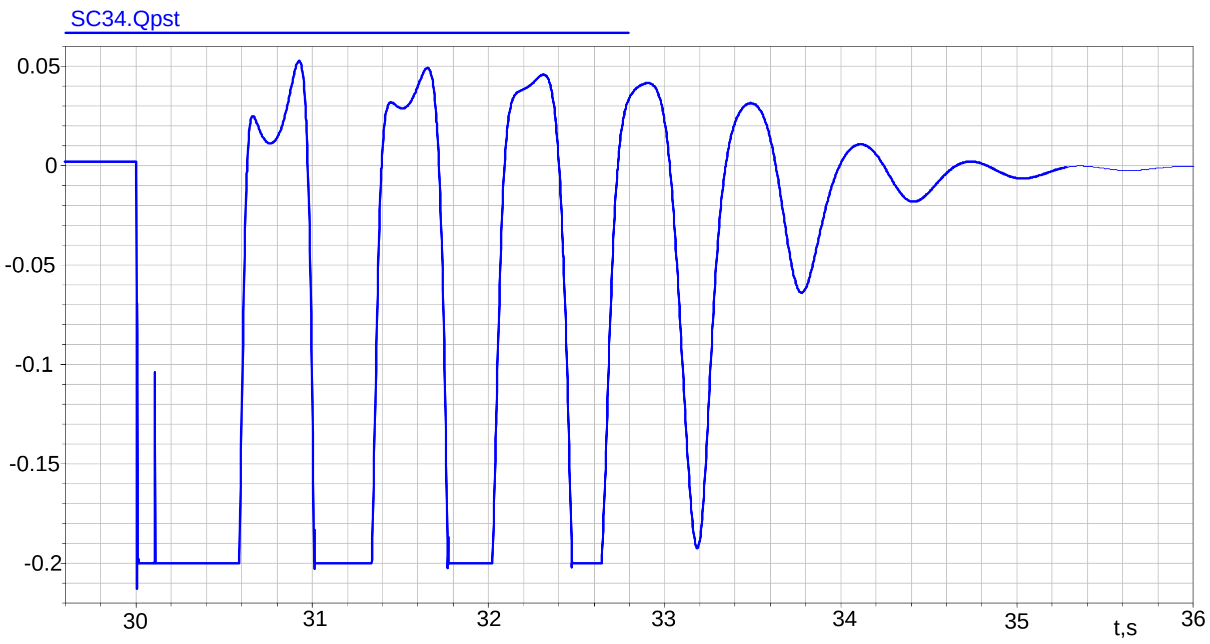


Figure 4. 13. Changes of the reactive power of the SSSC during the transient process

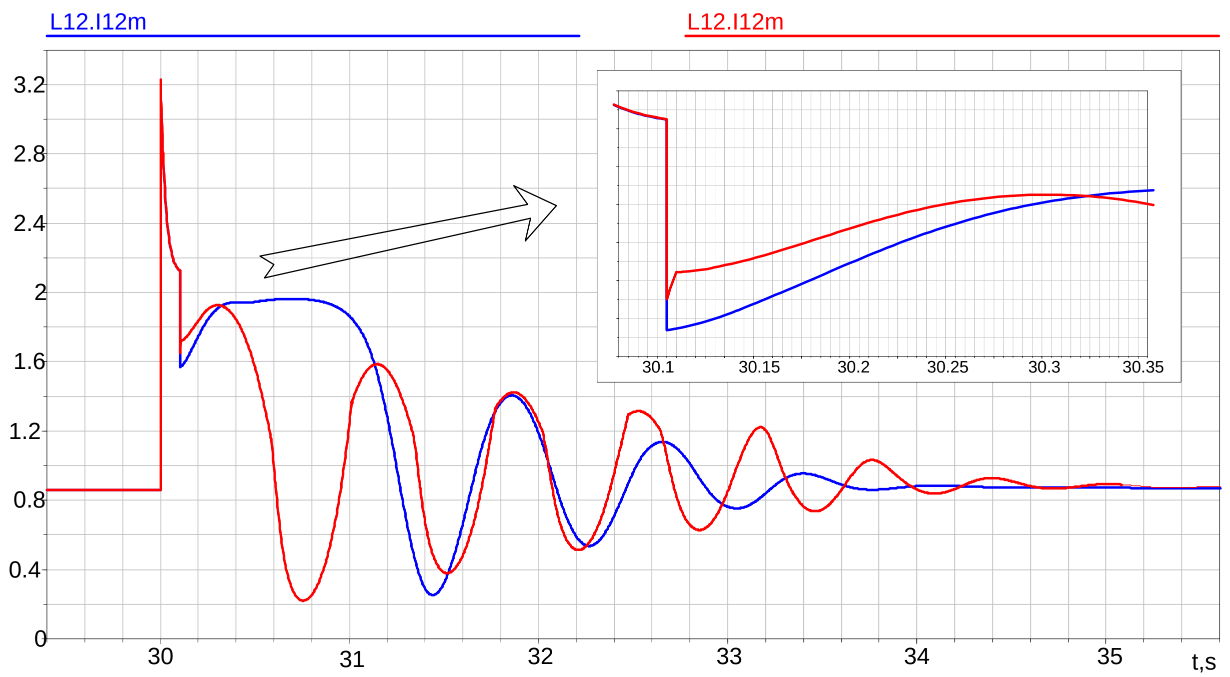


Figure 4. 14. Changes of the generator current without SSSC (blue curve) and with (red)

The Figure 4. 15 depicts the changes in voltages at SSSC terminals with the duration of short circuit 0.115 s (critical fault clearance time). Fluctuations of the voltage does not exceed the maximum voltage operating value for 500 kV – 525 kV (Standart 1516.1-76., n.d.). However, with the short-term duration the value may be surpasses by the value specified in (Khalilov, 2012).

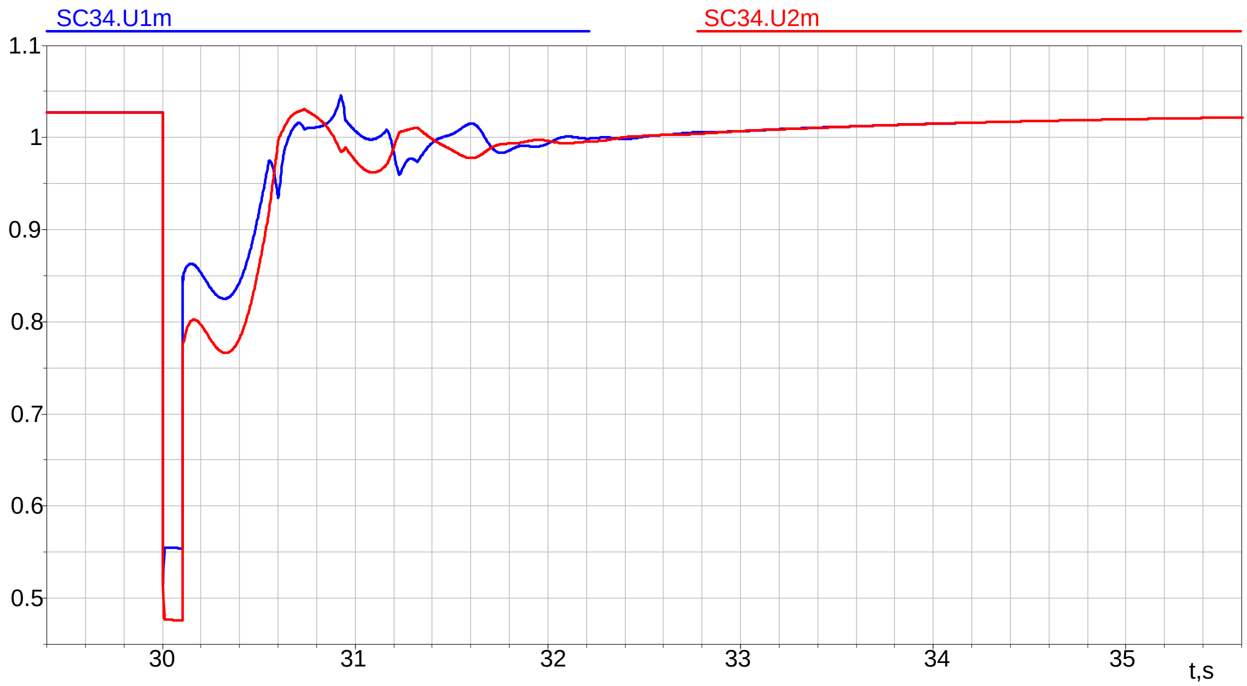


Figure 4. 15. Changes of voltage at the SSSC terminals from the transmitting side (blue) and receiving side (red)

4.5.Comparison of the effect on critical fault clearance time with a static synchronous compensator

To change inherent electrical characteristics of the EPS the shunt compensating device can be used. The analogue of the SSSC in this line of facilities is static synchronous compensator (STATCOM), which performs the following functions in the system:

- Maintaining the required voltage level at the point of connection,
- Increasing the line transmission capacity,

- Improving stability during transient processes.

As a result, it is important to compare the efficiency of these devices on the on critical fault clearance time.

STATCOM regulation is performed via the voltage deviation channels (the mathematical STATCOM model provided in Appendix A). Slip/frequency deviation channels are not considered. The results are presented at Figure 4. 9. As the rated power of the SSSC increases, its effect on the critical fault clearance time grows. In accordance with the adopted regulation law on voltage deviation, the generation of reactive power has a positive impact on voltage stabilization at the connection point (in the middle of the line). However, with the unit capacity less than 0.15 p.u. the produced effect has a slighter weaker influence then the SSSC.

Table 4. 8. Impact of the SSSC and STATCOM on the short-circuit duration

S_{SSSC},	Regulation	Δt_{SC}, s	$S_{STATCOM}$,	Regulation	Δt_{SC}, s
SSSC			STATCOM		
0.05	K_{0i}=10	0.107	0.05	K_{0u}=-10	0,106
0.1		0.110	0.1		0,109
0.15		0.112	0.15		0,113
0.2		0.115	0.2		0,116
0.25		0.117	0.25		0,120
0.3		0.118	0.3		0,125

4.6.Chapter summary

The following conclusions can be drawn from the tasks studied in this chapter:

1. The main patterns showing the impact of the SSSC on the single power transmission mode have been established. The inductive or capacitive compensation mode noticeably affected the voltage at the beginning and the end of the line. These results

confirm the efficiency of the device use for increasing the line transfer capacity and for the power flows redistribution.

2. The impact of the SSSC on the critical fault clearance time has been studied. It is obtained, that negative coefficient of current deviation has a deteriorative influence on transient properties of the system. Thus, in case of disturbances, the device should be switched off or be gone to the mode with the positive sign of the coefficient.
3. The positive current deviation channel has an affirmative effect on the transient stability of the system in question. Nevertheless, comparison with STATCOM shows that for the higher rated power installations, the efficiency of the shunt connected device is higher.

Chapter 5

Effect on the oscillatory steady-state stability

The increase of power units’ capacities and their remoteness from consumers are reasons for the increased value of transmission lines length, which leads to the deterioration of conditions for maintaining the stable synchronous operation of the EPS. Changes in loads, generation, and circuit-modes procedures (such as opened lines) result in different system performance as well as to the occurrence of weakly attenuating electromechanical oscillations.

Thus, the power system operation is accompanied by low-frequency oscillations conditioned by mutual hunting of generator rotors. These oscillations are able to reduce the value of the maximum allowed power flow, can be dangerous for the equipment, and cause a stable synchronous operation disturbance, as a result, to interrupt the power supply. The main reasons that contribute to the development of low-frequency oscillations are incorrect adjustment of regulators and the approach of operation mode to the steady-state stability margin. (Rogers, 2000) (Zaharov, 2013) (Sorokin, 2013)

The attenuation degree of theses vibrations varies considerably in relation to the characteristics of generators and loads in different modes. Regardless of these oscillation sources, they negatively impact the EPS characteristics. Therefore, an essential factor in the oscillation damping is the adjustment of the control systems used. (Zaharov, 2013)

The use of series connected FACTS devices likewise has a beneficial effect on the oscillation smoothing, since these facilities are equipped with automatic regulators (AR) whose setting parameters directly affect the fluctuating properties of the system. The selection and optimization of SSSC control channels coefficients will effectively increase the damping properties of the system. However, an inaccurate tuning of these controllers, as well as for

AER with strong actions, can cause the emerge of undamped oscillations in the EPS. (Sorokin, 2013)

Active and adaptive control of system parameters allows to improve power transmission characteristics. As a consequence, this chapter assesses the effectiveness of the co-utilization of the SM and SSSC regulators to improve system vibration damping.

5.1. Adjustment of the SM AER with strong actions

The value of the AER with strong actions coefficients (presented in section 3.1) determines the device influence efficiency on electromechanical oscillation damping. However, the tuning of the SM regulator channels is a complicated task, which depends on the parameters and characteristics of the EPS. Therefore, in this work, the coordination of the controller's settings via stabilization channels was performed in the vicinity of one steady-state mode, where the choice was made according to the stability and vibration damping conditions.

The calculation of the eigenvalues of the state variable matrix, which corresponds to the linearized equations of the system transients, is a visible representation of the parameters optimization approach of the SM regulator. The obtained eigenvalues vector has the following form (Belyaev, et al., 2017):

$$\lambda = \alpha \pm \beta$$

Where α determines the oscillation damping and β defines the frequency. The number of system solutions corresponds to the differential order of the model described.

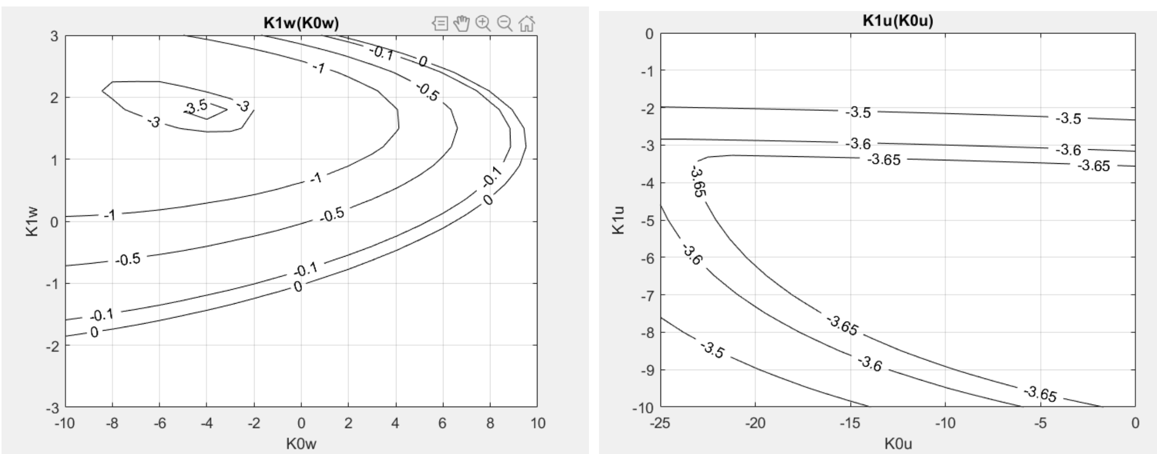
Another stability and quality analysis of transient processes classical approach is the frequency-domain D-decomposition method, the principle of which is to create stability areas relatives to the optimized parameters. The stability region is a line of equal damping – α, which is obtained for the tunable parameters with frequency variation β from 0 to 30 rad/s that corresponds to the range of the electromechanical oscillations. (Gryazina, et al., 2007)

Special attention is paid to the frequency range of the electromechanical vibrations' existence since their presence in the EPS complicates the choice of the regulator stabilization channels value. To estimate the efficiency of the applied influence, the root of the characteristic equations for the initial settings are given in Table 5. 1 (only the root with the lowest damping is presented). Quite high frequency of rotor oscillations is conditioned by the lowered magnitude of the mechanical inertia constant.

Table 5. 1 Characteristic roots for AER setup: K_{0u}*=-25,* K_{1u}*=-1,* $K_{0\omega}$*=-1,* $K_{1\omega}$*=1,5,* K_{if} *=-1*

Real part – α, 1/s	Imaginary part – β, 1/c
-1,7	9,7

Synchronous generator AER settings optimization was realized by means of the D-decomposition method. Where at the first adjustment stage the influence of voltage deviation gain on vibration damping was studied. On the basis of the obtained data proportional and derivative gains of the frequency and excitation current proportional gain were determined. The drawing of the attenuation curves in the plane of stabilizing parameters was conducted in several iterations based on values obtained on the previous stage. An example of equal damping curves at the last stages of optimization is shown in Figure 5. 1. The value for obtained tuning gains are shown in Table 5. 2.



a) b)

Figure 5. 1. Curves of equal attenuation in the plane of stabilizing parameters ($K_{0\omega}$ *and* $K_{1\omega}$ *– a,* K_{0u} *and* K_{1u} *– b)*

Table 5. 2. Tuning coefficients of the AER

Abbreviation	K_{0u}	K_{1u}	$K_{0\omega}$	$K_{1\omega}$	K_{if}
Value	-18	-6	-4,5	1,8	-3

The roots of the characteristic equation corresponding to these settings are -3.69±6.05 1/s and -4.02±10.55 1/s. The attenuation of oscillatory processes at low perturbation will be no worse than from the time constant (τ) equal to 0.271 c, (τ=1/ α). The change in electromagnetic power at low perturbation is shown in Figure 5. 2. Oscillation attenuation is accomplished in 3-5 τ ~1.084 s.

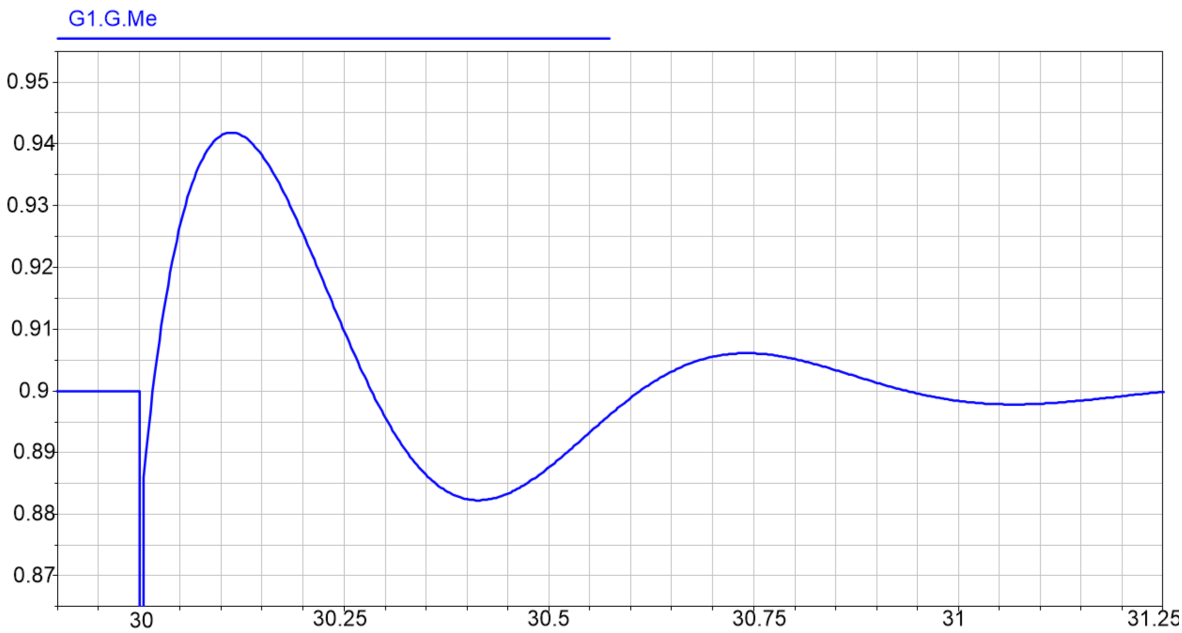


Figure 5. 2. Changes of generator electromagnetic power

5.2. SSSC regulator adjustment

SSSC fast response provides an opportunity to actively influence the stability indicators of low perturbed movement in an electric network. This ability of the FACTS devices arises from the capability to control interrelated grid parameters, such as voltage, transmission angle, and reactive power.

The SSSC was controlled by the line current proportional gain (K_{0i}), as well as proportional and derivative gain of generator rotor slip (K_{0s} and K_{1s}) or voltage frequency at connection point (K_{0f} and K_{1f}).

5.2.1. Generator rotor slip control

The method of simultaneous coordination of controller settings on the basis of numerical search (in the MatLab software environment) is used as a method of SSSC tuning parameters optimization within this research. The major merit property of this method is the ability to use a large number of optimization variables. As a fitness function, the sum of the difference between the defined attenuation index (α_{min}) and all roots lying to the right of α_{min} is used. (Belyaev, et al., 2017)

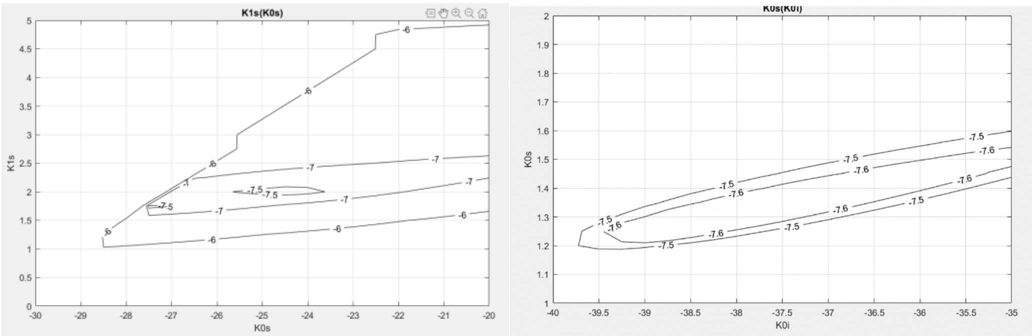
$$F = \sum_{\alpha_i \leq \alpha_0} (\alpha_0 - \alpha_i)^v$$

Where α_0 is specified value of the quality index, α_i is real roots taken with a reversed sign, v is a parameter (v=2, 3,…).

Table 5. 3. Characteristic equation's roots for AR with rotor slip control channels

K_{0i}=-5, K_{0s}=- 24,95 and K_{1s}=1,95		K_{0i}=5, K_{0s}=- 39 and K_{1s}=1,25	
α, 1/s	jβ, 1/s	α, 1/s	jβ, 1/s
0	0	0	0
0	0	0	0
-0.527	0	-0.501	0
-1.690	0	-1.606	0
-2.321	0	-2.219	0
-7.759	±9.584	-7.871	±10.312
-7.786	±12.317	-7.961	±11.031
-10	0	-14.286	0
-14.286	0	-14.286	0
-14.286	0	-14.286	0

This technique has shown high efficiency of the device stabilization channels attraction. The obtained results indicate an insignificant dependence of the current proportional gain on vibration damping. The same value of attenuation can be achieved for both modes of operation (positive and negative value of the coefficient) with corresponding changes in deviation and derivative generator rotor slip channel. The attained roots of the characteristic equations for the negative current gain and positive presented in Table 5. 3. All the data are for the 0.2 rated power.



a) *b)*

Figure 5. 3. Transmission stability area with SSSC a) negative sign, b) positive sign

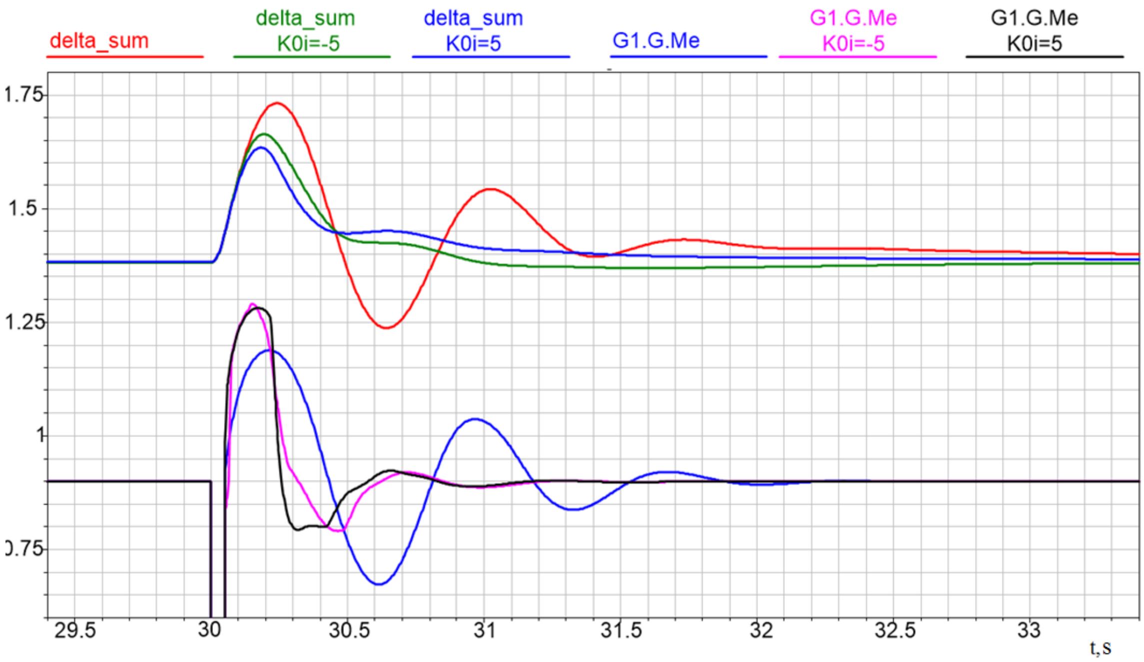


Figure 5. 4. Changes in transmission angle and electromagnetic power without SSSC (red and blue curve), with SSSC and negative sign (green and pink) and with positive sign (blue and black)

In accordance with table 5.3, a damping rate of α=-7.79 1/s has been achieved, compared to α=-3.69 1/s for a network without SSSC. The stability areas in Figure 5. 3 show the validity of the results obtained. Figure 5. 4 illustrates the behavior in variables with and without the series connected device.

The joint tuning of the SSSC and SM controllers has resulted in even higher attenuation rates, the value of which are shown in Tables 5.4 and 5.5. The damping value of -14.2 1/s is provided for negative current gain and 14.3 1/s for positive. The comparison of results from tables 5.4 and 5.6 shows that a pair of complex-conjugated roots degenerate into negative real roots, which determines the aperiodic stability of the system.

Table 5. 4. Characteristic equations roots at a joint adjustment of AER with K_{0u}=-18, K_{1u}=-6, $K_{0\omega}$=-6,05, $K_{1\omega}$=-0,215, K_{if} = - 3 and AR with K_{0i}=-5, K_{0s}= - 33,5 and K_{1s}=0,37

α, 1/s	jβ, 1/s
0	0
0	0
-0.514	0
-2.348	0
-3.406	0
-5.689	0
-10	0
-10.456	0
-14.286	± 1.23e-07
-14.551	±4.787

Table 5. 5. Characteristic equations roots at a joint adjustment of regulators for AER with K_{0u}=-18, K_{1u}=-6, $K_{0\omega}$=-5.4, $K_{1\omega}$=-0,2, K_{if} = - 3 and AR with K_{0i}=5, K_{0s}= - 51 and K_{1s}=-1.2

α, 1/s	jβ, 1/s
0	0
0	0
-0.498	0
-1.871	0
-3.796	0
-5.65	0
-10	0
-10.376	0
-14.286	0
-14.286	0
-14.374	±3.978

Figure 5. 5 depicts plots of the changes in transmission angle and electromagnetic power for the negative current gain and its corresponding rotor slip stabilization channels. Red and blue curves illustrate the behavior of variables at optimal SM AER settings, green and pink at optimal SSSC settings, and blue and black with joint optimization of parameters. The attenuation of the generator electromagnetic power is characterized by almost aperiodic nature for the gain joint tuning. It should be noted that the adjustment of stabilization channels was made to represent the potential capabilities of the device.

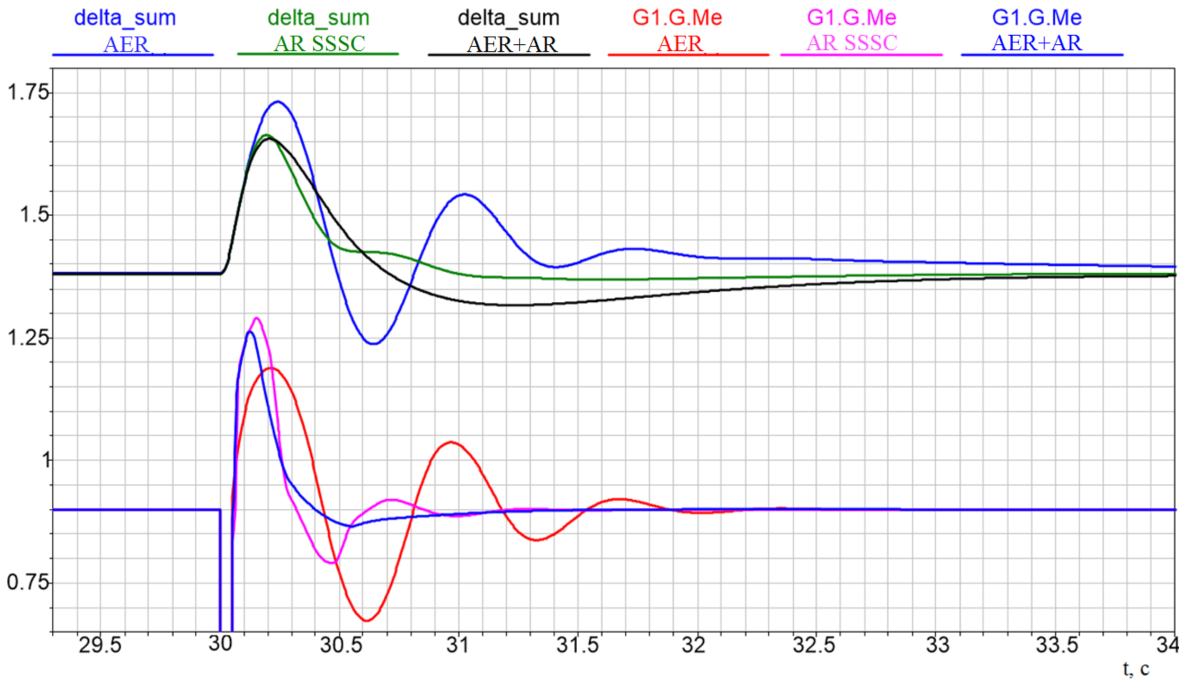


Figure 5. 5. Changes in transmission angle and electromagnetic power for different stabilization channels of the SM and SSSC

5.2.2. Voltage frequency at point of connection control

Regulation by proportional and derivative generator rotor slip gains is artificial (theoretical) stabilization method and is not applied in practice. In real operating conditions, especially in a multi-machine circuit, the transfer of the generator rotor slip signal to the SSSC regulator unit is a complicated task. Therefore, the deviation and derivative voltage frequency channels are considered as stabilizing parameters.

The search analysis of the optimal attenuation degree has shown that the same damping index can be reached for different values of current proportional gain with the corresponding frequency proportional gain. However, the derivative channel does not have a significant effect on the oscillation damping. Those features are shown in Table 5. 6. The following SSSC controller settings were chosen: $K_{0i}=-5, K_{0f}=-0.26$ and $K_{0i}=5, K_{0f}=-0.17$. The roots of characteristic equations corresponding to these parameters are given in Table 5. 6. The damping factor is about 4.5 1/s.

Table 5. 6. Characteristic equation's roots for AR

K_{0i}=5, K_{0f}=- 0.23		K_{0i}=5, K_{0f}=- 0.15	
α, 1/c	jβ, 1/c		
0	0	0	0
0	0	0	0
-0.493	0	-0.454	0
-1.230	0	-1.154	0
-4.608	± 3.917	-4.487	±11.637
-5.189	± 11.422	-4.819	±5.312
-10	0	-9.799	0
-10.611	0	-10	0
-14.286	0	-14.286	0
-14.286	0	-14.286	0

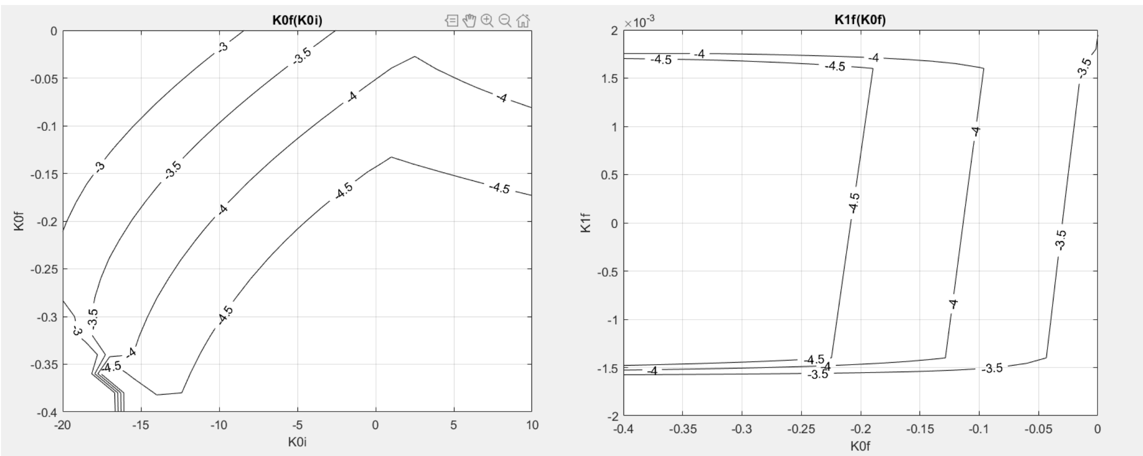


Figure 5.6. Transmission stability area

Figures 5.7 and 5.8 demonstrates the electromagnetic power and transmission angle curves with the use of SSSC and without. Different behavior of curves with positive and negative control gain is explained by roots values. The smallest damping index corresponds to the fluctuations with different frequencies.

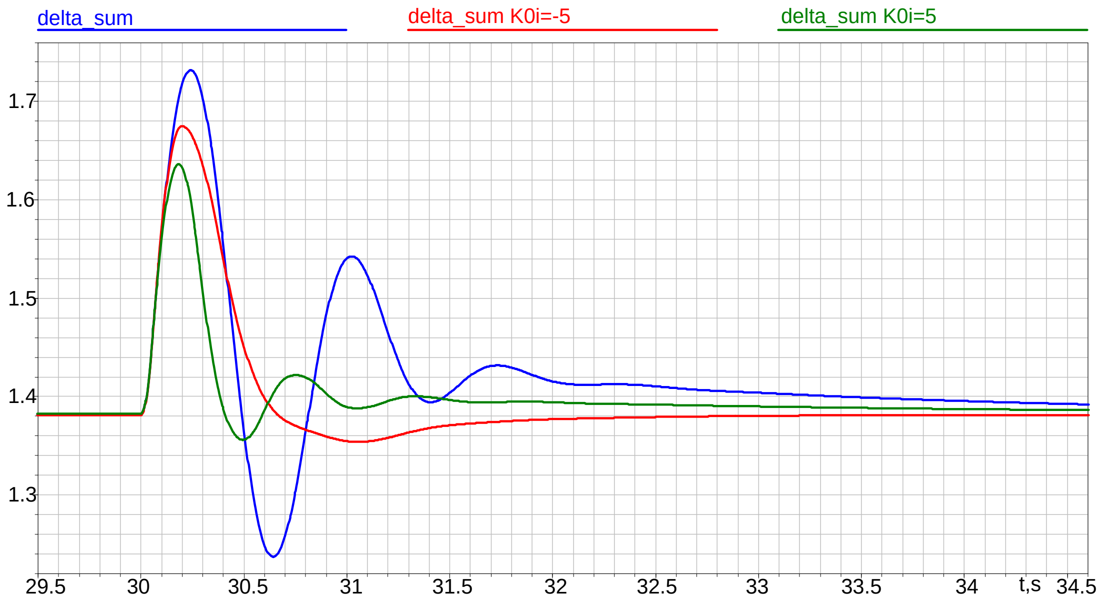


Figure 5.7. Transmission angle behavior without SSSC (blue curve), with K_{0i}=-5 (red), K_{0i}=5 (green)

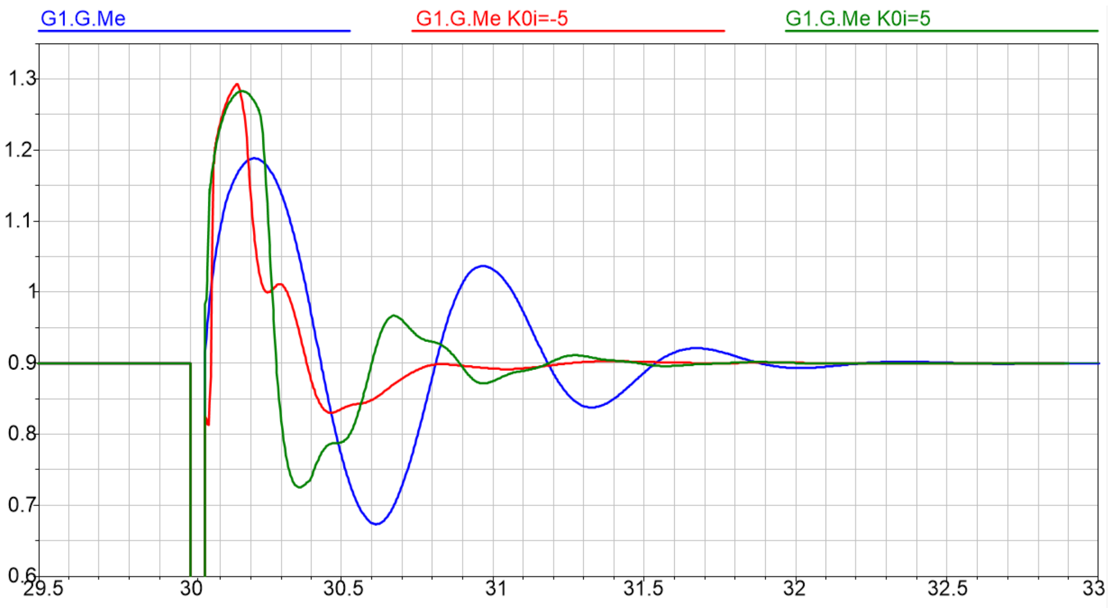


Figure 5 8 Electromagnetic power behavior without SSSC (blue curve), with K_{0i}=-5 (red), K_{0i}=5 (green)

The joint adjustment of the SM and SSSC leads to the higher damping indices, whose value are shown in Table 5.7 and 5.8. However, the achieved results do not coincide for the different sign current gain. At K_{0i}=-5 damping degree is -6.01, while for K_{0i}=5 is -5.43.

Table 5. 7. Characteristic equations roots at a joint adjustment of regulators for AER with K_{0u}=-18, K_{1u}=-6, $K_{0\omega}$=-2.675, $K_{1\omega}$=1.3, K_{if} = - 3 and AR with K_{0i}=-5, K_{0f}= - 0.26

α, 1/c	jβ, 1/c
0	0
0	0
-0.506	0
-1.129	0
-5.978	±7.954
-6.013	±6.059
-9.583	0
-10	0
-14.286	0
-14.286	0

Table 5. 8. Characteristic equations roots at a joint adjustment of regulators for AER with K_{0u}=-18, K_{1u}=-6, $K_{0\omega}$=-3.35, $K_{1\omega}$=1.36, K_{if} = - 3 and AR with K_{0i}=5, K_{0f}= - 0.15

α, 1/c	jβ, 1/c
0	0
0	0
-0.459	0
-1.112	0
-5.435	±7.819
-5.442	±8.357
-9.393	0
-10	0
-14.286	0
-14.286	0

Figure 5.9 illustrates the transient process behavior with K_{0i}=5, K_{0f}= - 0.15, and corresponding AER parameters. The same nature of the curves with the SSSC (initial and optimal tubed AER gains) at a time interval up to 30.4 s is due to the fact that generator excitation voltage reaches its limit. Thus, the damping properties of the new AER coefficients appear after the limiting of excitation voltage fluctuations.

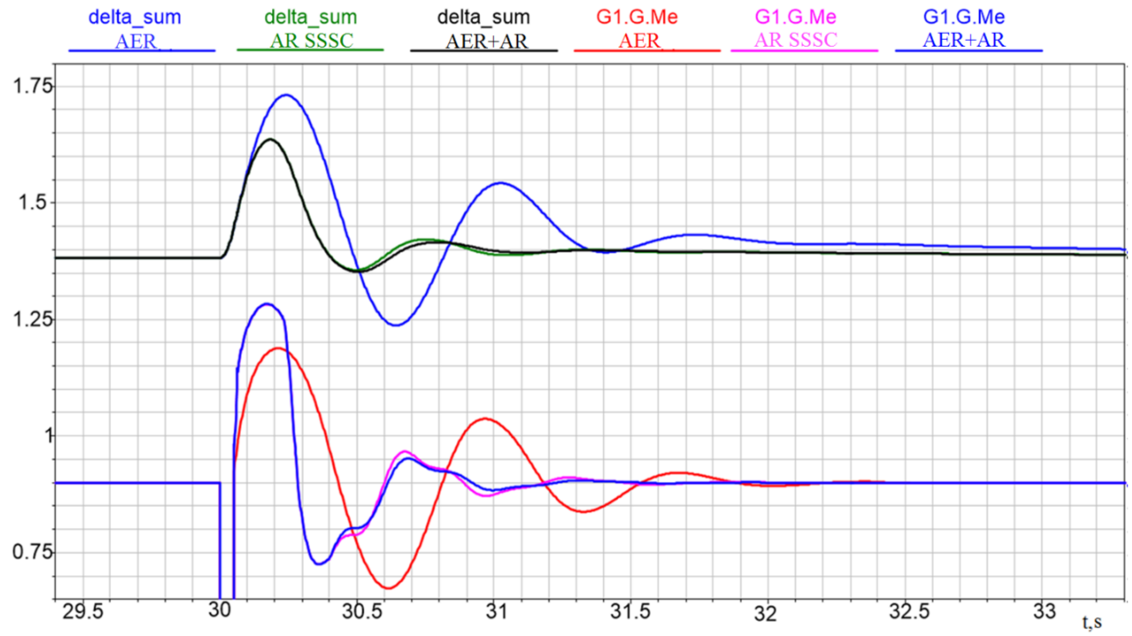


Figure 5.9. Changes in transmission angle and electromagnetic power with positive K_{0i}

5.2.3. Comparison of the stabilization channels efficiency

Comparing the impact of two types of SSSC stabilization channels: proportional and derivative generator rotor slip gains (Figure 5. 5) and proportional voltage frequency at the point of connection channel (Figure 5.9), it can be noted the deterioration of the damping characteristics with the use of voltage frequency gain. This effect is associated with a delay in the response of voltage frequency in relation to the slip gains, which leads to a signal delay and a decrease in the control effect amplitude.

5.3. Chapter summary

Based on results obtained, the following conclusions can be drawn about the impact of the SSSC device on vibration damping performance:

1. Regulations additional channels by generator rotor slip and voltage frequency have a essential effect on the quality of the transient process. With the help of the D- decomposition method and the method of the control settings simultaneous

coordination the optimal values for stabilization channels coefficients have been found to improve system attenuation indices. The joint adjustment allows to achieve higher values.

2. Improvement of the damping properties of the system occurs for both SSSC operation modes. Depending on the gain sign, the associated SSSC controller parameters should be changed.

Conclusion

In the presented master's thesis work, the installation of the SSSC device in the middle of a single power transmission circuit was considered. The method of mathematical modeling of the facility is based on the representation of the SSSC by an adjustable source of emf with stabilization channels by deviation and derivative of generator rotor slip of voltage frequency at the point of connection, as well as the current deviation.

The investigated mathematical model has allowed to establish the basic patterns of series FACTS device influence on power transmission operation modes. Generation of the additional voltage in the line results in an increase of the shift angle between transmitting and receiving system, and as consequence, in a decrease value of the line transfer power limit. In contrast, when a part of the voltage drop is compensated, the power transfer limit increases due to decline of the angle value. Thus, the effect of power flows redistribution and transmission line optimal loading (up to the thermal current limit) is visually illustrated.

The impact estimation of regulation channels on transient processes, namely on critical fault clearance time, was made. The obtained data have shown that the negative sign of the current proportional gain reduces fault clearance time. On the other hand, the positive coefficient contributes to the value increase. Therefore, during the current limiting mode of the SSSC, the device should be brought out of service or be switched to the mode with the positive current proportional gain. However, the SSSC analogue in shunt connected FACTS device range – STATCOM is more effective in enhancing transient stability with a growing rated power value of a unit.

It is shown that SSSC performs an effective influence on vibration damping in the power system at low disturbances for both operation modes. The sign and the value of the current gain determines the corresponding slip of frequency regulator settings. As a result of the controller settings parameters, it has been demonstrated that the joint adjustment of the SM and SSSC regulators provides possibilities for achieving high attenuation values.

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Appendix A

The following mathematical model of the STATCOM was used to perform calculations of electromechanical transient processes. The input variable is the voltage at the point of connection, which is determined by projections on q,d coordinate axes. The rated power is assigned in input data. (Eremia, et al., 2016) (Padiyar, 2007) (Belyaev , et al., 2012) (Kochkin & Shakaryan, 2011)

The STATCOM emf increment is calculated by the use of following transfer function:

$$\Delta E_{ST} = \frac{K_{st} \cdot \left(U_{st} - U_{setpoint}\right)}{1 + pT_{0u}};$$

Where K_{st} – voltage proportional gain ($K_{st} = -5 \ldots$ – 100 emf STATCOM units / voltage unit),

T_{0u} – time constant of voltage proportional gain,

$U_{setpoint}$ – voltage setpoint.

Since the mathematical model of STATCOM is described by the use of the d,q coordinate system, the emf incremental coefficients are calculated in q,d axes:

$$\left.\begin{aligned} K_q &= \frac{|U_q|}{U_{st}} \\ K_d &= \frac{|U_d|}{U_{st}} \end{aligned}\right\}$$

Components of the STATCOM currents are calculated in accordance with the relations between the emf components at its terminals:

$$I_{qst} + jI_{dst} = \left(E_{qst} + jE_{dst} - U_q - jU_d\right) \cdot jb_{st}$$

Therefore

$$I_{qst} = -b_{st} \cdot (E_{dst} - U_d) \cdot$$

$$I_{dst} = b_{st} \cdot \left(E_{qst} - U_q\right) \cdot$$

Expressions in parentheses are projections of STATCOM emf increments on q,d coordinate axes. Thus, the current components are calculated by expressions:

$$I_{qst} = -b_{st} \cdot \Delta E_{ST} \cdot K_d \cdot sign(U_d) \cdot$$

$$I_{dst} = b_{st} \cdot \Delta E_{ST} \cdot K_q \cdot sign\left(U_q\right) \cdot$$

The value of the emf increment is limited in such a way that the STATCOM current module equal to the $b_{st} \cdot \Delta E_{ST}$ cannot exceed the rated (set) power value of the device.

Direct use of current calculations results by algebraic equations in the balance of currents at point of connection leads to the computational instability. Therefore, value involved in the computational process are determined using transfer functions:

$$I_{qst\ c} = \frac{I_{qst}}{1 + pT_s}$$

$$I_{dst\ c} = \frac{I_{dst}}{1 + pT_s}$$

Where $T_s$is a time constant which determines the STATCOM's response delay to the change in the control effect on the emf regulator channel.

Appendix B

Scripts in the MATLAB software

In the MATLAB software, built-in functions of the Dymola software (such as initload, parload and etc.) were used in the script.

Eigen values calculation:

```
Tmax = 50;
[x0,n_X0]=initload; [p,n_par]=parload; p1=p; x0z=x0;
[s1,n1] = dymosim([0,Tmax,0,50000,1.e-6,8], x0, p);
Nmax = size(x0,1); x0=(s1(size(s1,1),2:Nmax+1)).';
dyn_in_create([0,50,0,50000,1.e-6,8], x0, p);
eval( ['! C:\SSSC\Mfiles\traj\alist.exe -a dsin.mat dsin.txt'] );
!dymosim -l
load dslin
format long g
flipud(esort(eig(ABCD)))
```

D-decomposition method:

```
x1=-60; x2=-40; y1=-2; y2=0;
[X,Y]=meshgrid(x1:(x2-x1)/20:x2,y1:(y2-y1)/20:y2);
Zap=zeros(size(X)); Zosc=zeros(size(X)); ZW=zeros(size(X));
[p,n_par]=parload; [x0,n_X0]=initload;
```

```
for k1=1:size(Zap,1)
  for k2=1:size(Zap,2)
    p(51)=X(k1,k2);
    p(52)=Y(k1,k2);
    dyn_in_create([0,10,0,2000,1.e-6,8], x0, p);
    eval( ['! C: \SSSC\Mfiles\traj\alist.exe -a dsin.mat dsin.txt'] );
    apf1; Zap(k1,k2)=alfa; Zosc(k1,k2)=alfa1; ZW(k1,k2)=beta1;
end
end
[c,h]=contour(X,Y,Zosc,[-13 -12  -3 -4.5 0]);clabel(c,h);colormap([0 0 0]);
grid; xlabel('K0f'); ylabel('K1f'); title('K1f(K0f)')
```

Method of the regulator control settings simultaneous coordination:

```
global x0 p alpha_min;
alpha_min=-5; Coeff_Start=zeros(2,1);
LB=[ -10; -10];
UB=[30; 0];
Options = optimset('Diagnostics','on','MaxFunEvals',5000);
Coeffs_New = fmincon('opt_root_G', Coeff_Start, [],[],[],[],LB,UB,[],Options);
function Sol=opt_root_G(X)
global x0 p alpha_min;
p(45) = X(1); p(16) = X(2); %as an example
dyn_in_create([0,10,0,500,1.e-6,8], x0, p);
eval( ['!C:\SSSC\Mfiles\traj\alist.exe -a dsin.mat dsin.txt'] );
!dymosim -l
```

```
load dslin; Vse_Korni=esort(eig(ABCD));
Sol=0;
for k=1:length(Vse_Korni)
  if real(Vse_Korni(k))>alpha_min
    Sol=Sol + (real(Vse_Korni(k)) - alpha_min) ^ 2;
  end
end
```