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Modeling and Simulation of FACTS and HVDC Controllers in MATLAB/Simulink for an institute's Lab

Master Thesis

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Declaration:

I hereby declare that I have written this work independently and used no more sources otherwise I announced it as references in this master thesis.

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Abstract

The prompt evolution on electrical power consumption has been required a power system revision in order to match power system capacity with load demands under contingency perturbation of system further normal condition. Hence, utilization of some different types of controller is vital to adjust system parameters on desired state of existence. As the most practical modern compensators which can interact with system alteration expeditiously due to their power electronic valves' capabilities, FACTS devices and HVDC technologies could advance power systems performance and maintain them in the stable domain where have been implemented worldwide.

In the present thesis, various FACTS controllers are considered and compared to evaluate their effect on power transmission capacity enlargement in addition to voltage and transient stability improvement in the case of power system institute's laboratory with specific practical weaknesses to provide proper compensator to complete the laboratory's facility for future.

The main focus is the performance analysis of designed devices on system constraints in issue of voltage and transient stability. As shunt connected FACTS devices, SVC and STATCOM are considered in the weakest point of the line for two simple configuration of laboratory experimental test. In the first configuration that load connection is regarded, they mostly compensate reactive power insufficiency of system and achieve to advanced voltage collapse point. For the second arrangement with conjunction to the university network, these controllers are employed to maintain system on proper stable domain after disturbance occurrences in addition to keep voltage level of all system buses on the appropriate constant value. Moreover, SSSC and UPFC influences on system behavior in the case of voltage and transient stability are examined for both configurations to probe qualification of mentioned shunt-connected controllers in comparison to them. Besides, as an instance of HVDC impression on behavior of system, CSC-HVDC is investigated in the second configuration.

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List of Abbreviations

AC	Alternative current
CPF	Continous Power Flow
CSC	Current Source Converters
DC	Direct Current
ESCR	Effective Short Circuit Ratio
FACTS	Flexible AC Transmission Systems
GTOs	Gate Turn Off Thyristors
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IGBTs	Insulated Gate Bipolar Transistors
IPFC	Interline Power Flow Controller
MOV	Metal Oxide Varistor
P.f	Power factor
PSAT	Power System Analysis Toolbox
PST	Phase-Shifting Transformer
PWM	Pulse Width modulation
p.u.	Per Unit
SIL	Surge Impedance Load
SSSC	Static Series Synchronous Compensator
SSR	SubSynchronous Resonance
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVS	Static Voltage Source
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Compensator
TSR	Thyristor Switched Reactor
TSC	Thyristor Switched Capacitor
UPFC	Unified Power Flow Controller
VSC	Voltage Sourced Converter

List of Symbols

α	Firing delay angle
α_{TCR}	Firing delay angle of TCR
β	Spatial angle factor
ε	Ratio of network voltage to AC source voltage as excitation voltage
δ	Phase angle
σ	Conduction angle
φ	Difference phase angle between UPFC output voltage and line voltage
λ	Loading parameter
$\underline{\gamma}$	Propagation constant
ξ	Difference phase angle between STATCOM output voltage and line voltage
ζ	Extinction angle of valves for inverter
μ	Overlap angle of simultaneous commutated valves
ω	Angular frequency
ω_{r}	Rotor Speed
θ	Difference phase angel between a-axis in abc frame and d-axis in dq0 frame-work
a, b, c	Phase a, b, and c of three phase system
$\underline{A}$	VSC gain
B	Susceptance
B_{SVC}	Susceptance of SVC
C	Capacitance
G	Conductance
h	Counter variable for harmonics
$\underline{I}$	Current
I_{r}	Reactive current exchange
I_{ref}	Reference current
$I_{\mathrm{r\_STATCOM}}$	Reactive current exchange of STATCOM
I_{r1}^{6}	Reactive current fundamental frequency of six-pulse VSC
$I_{\mathrm{r}h}^{6}$	Reactive current harmonics of six-pulse VSC
$\underline{I}_{\mathrm{R}}$	Current in receiving point of network
$\underline{I}_{S}$	Current in sending point of network
$\underline{I}_{\mathrm{SVC}}$	SVC current exchange

$\underline{I}_{\mathrm{TCR}}$	TCR current exchange
K_{TCSC}	Ratio of TCSC's reactance to line's reactance
l	Length of the line
L	Inductance
n	Transformer turn ratio
P	Active power
P_0	Load active power at nominal voltage
P_{e}	Electrical power
P_{m}	Mechanical power
P_{ref}	Reference active power
Q	Reactive power
Q_0	Load Reactive power at nominal voltage
Q_{ref}	Reference reactive power
R	Resistance
R_{a}	Total internal resistance of generator in simple model
S	Apparent power
$\boldsymbol{T}_{\mathrm{abc/dq0}}$	Park's transformation matrix from abc frame to dq0 frame
$\underline{U}$	Voltage
$\underline{U}_0$	Nominal voltage
U_{dc}	DC voltage
U_{m}	Voltage in midpoint of network
$\underline{U}_{\mathrm{p}}$	AC source voltage
U_{P1}^{6}	Reactive voltage fundamental frequency of AC output source of six-pulse VSC
U_{r}	Reactive voltage exchange
U_{ref}	Reference voltage
$U_{\mathrm{r\_SSSC}}$	Reactive voltage exchange of SSSC
$U_{\mathrm{r\_UPFC}}$	Reactive voltage exchange of UPFC
$\underline{U}_{\mathrm{R}}$	Voltage in receiving point of network
$\underline{U}_{\mathrm{S}}$	Voltage in sending point of network
X	Reactance
X_{C}	Capacitive reactance
X_{L}	Inductive reactance of the line
X_{s}	Total reactance of generator in simple model

X_{SSSC}	Total reactance of SSSC
X_{TCSC}	Total reactance of TCSC
X_{TCR}	Total reactance of TCR
$\underline{Y}$	Admitance
$\underline{Z}$	Impedance
$\underline{Z}_{\mathrm{c}}$	Characteristic impedance
$\underline{Z}_{n}$	Natural load
Z_{N}	Total network impedance

1 Introduction

Recently, AC transmission lines encounter more critical situations due to the load demand growth and inadequate power network capacity mainly for the long distance power transfers in vast distributed consumer areas. Thus, the most essential undertaking actions to seek proper power transmission and make network more reliable under unpredictable circumstances are revision and refinement of current power networks. In order to revise the transmission systems and avoid dispensable network restructure, utilization of some conventional controller types have been efficiently concerned. These controllers should be capable to alter the system characteristics through their parameters adaption to attain flexible operation of AC transmission lines under diverse consumption demands. In this way, power electronic based controller systems could be more supportive than other static controllers and traditional compensators to compensate insufficiency of power transfer capacity in addition to improvement of system stability.

Numerous Flexible AC Transmission Systems as the most practical power electronic based controllers have been applied in the modern transmission lines broadly in recent years due to their advanced influence on system stability reinforcement further power transmission enhancement. Besides, incorporation of HVDC technologies with FACTS devices employment could devise noticeable improvement on power systems performance specifically in the case of long distance transmission lines and prevent an unnecessary AC system deployment, which would result on unjustified economical investments.

Accordingly, for the case of practical laboratory to illustrate FACTS devices and HVDC technologies influence on power transmission enhancement and system stability, utilization of appropriate devices should be concerned to make feasible more experimental tests. So, in the first step, the various well-known parallel and series FACTS controllers and HVDC technology impression on laboratory system operation and principally their behavior on stability issue should be analyzed. Subsequently, the results will be compared in the purpose of laboratory's future plan to provide some more effective devices for learners' experimental tests as a practical system to indicate system instability prevention and power transferring enhancement in order to improve laboratory performance.

In this regards, as the first part of this thesis, essential elements of each power network will be explained in brief. The next section is allocated to introduce the FACTS controllers concisely which are categorized to shunt-connected, series-connected, and combined types to clarify the basic contents. Also, the main contexts of voltage and transient stability as the most issues on system stability in this case will be described. Subsequently, for the situation of institute's laboratory with particular specification which will be analyzed without compensation firstly, diverse FACTS devices influence on power system behavior in voltage stability issue in the case of simple radial system with load will be demonstrated and compared to illustrate an impressive reinforcement on voltage stability restriction nose point. Afterward, the system behavior analysis for the case of ending point connection to the university's network under three-phase fault occurrence as an instance of contingency disturbances will be investigated without and with consideration of various FACTS devices and CSC-HVDC technology with the intention of compare their qualification to advance system performance.

2 Theoretical Basics

2.1 Basics of Equipments

The main purpose of each three phase AC power system is the transfer of electrical power from generation stations as sending points to the consumption places as receiving points through different network structure such as radial, mesh or combination of both. The transfer occurs under specified voltage levels due to distance between the sending and receiving points which are classified as transmission, subtransmission and distribution system as seen in **Fig 2.1**.

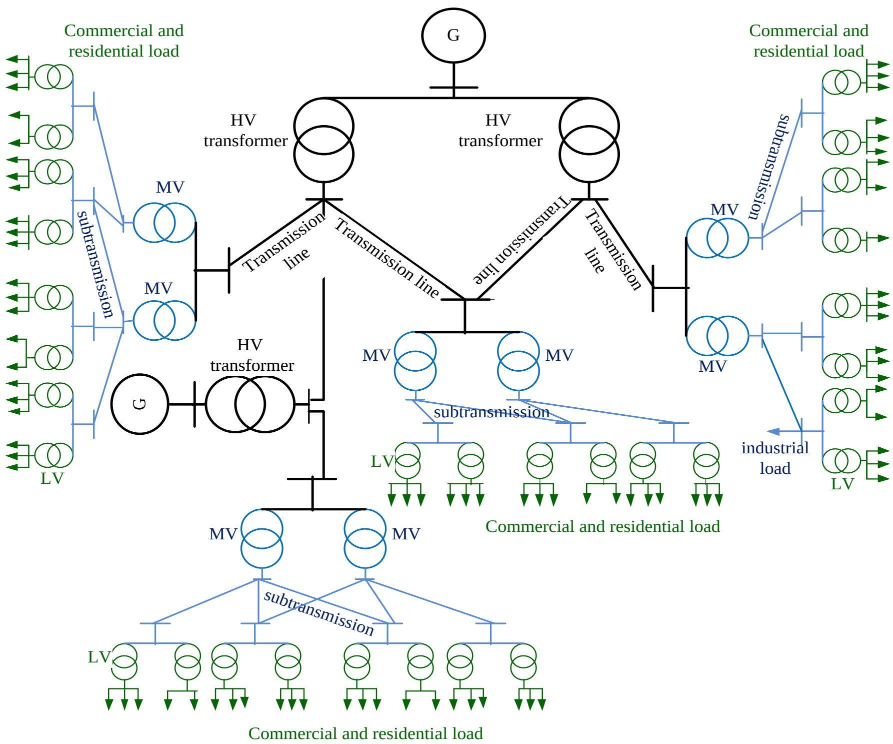

Fig 2.1 Basic structure of AC power system

The principal equipments of three phase AC power system to transport power in various voltage level comprise synchronous generators to supply required power with a high rated voltage for the rest of the system depending on the load demand, transformers which provide proper voltage level for each subsystem classification, transmission lines with diverse voltage and current levels sustainability fit in various subsystems, and loads which consist of different types of consumers such as a variety of three phase or single phase motors. In this section concise description of main elements are explained.

2.1.1 Synchronous Generator

In general, high rated power in each AC power system is produced via three phase synchronous generators. The typical structure of every synchronous generator comprises two parts, the turning part is called rotor includes field windings as an excitation circuit by DC current through various types of exciters. The static part which is known as stator whose armature windings are installed on it, so that produce magnetic poles identical to excitation windings poles on rotor. In other words, rotation of rotor in the first step initiates through the prime mover with controllable speed via a DC motor or different types of turbine. Subsequently, the uniform magnetic field around rotor which is produced via excitation current in the field windings is cut off with rotor and induces voltage into the armature windings according to Faraday's Law. Thus, AC current flow which its frequency is proportional to the rotor speed under steady state situation is generated in the armature windings and its magnetic field rotates with the same speed of rotor. This speed is known as synchronous speed. Furthermore, the excitation and prime mover (governor) controllers are employed to adjust the generator output voltage and frequency on the desired constant values.

Depend on rotor structure such as round, salient pole and cylindrical shape, steady state characteristics and generator application will be changed. For instance, salient pole which can be applied on low speed situation is utilized as hydroelectric generator in contrast to the round one as steam generator [7, 8].

In general, there are two practical models for every synchronous generator to analyze its steady state and transient behavior, simple model which is capable to evaluate generator behavior under steady state condition and dq0-model can be applied for both aims.

2.1.1.1 Simple model

In this model with assumption of symmetrical components for all three phases and simplification of internal circuits of generator with the synchronous generator reactance $X_\mathrm{s}$and total resistive losses R_a the simplified model for single phase can be shown by **Fig 2.2** and terminal voltage of the phase $\underline{U}$ can be calculated relevant to internal AC voltage source of generator, which is called here as excitation voltage,$\underline{U}_\mathrm{p}$by

$$\underline{U} = (R_\mathrm{a} + \mathrm{j}X_\mathrm{s})\underline{I}_\mathrm{a} - \underline{U}_\mathrm{p} \tag{2.1}$$

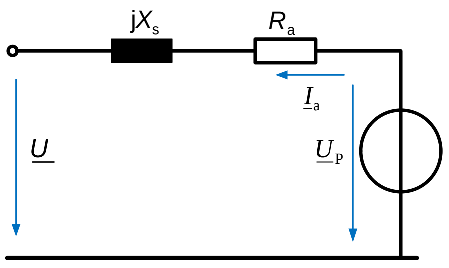

Fig 2.2 Simplified model of synchronous generator

If the terminal voltage of generator is considered as slack node with reference voltage amplitude, depiction of phasor diagram for various power factors as lead, lag and unity can be noted in **Fig 2.3**.

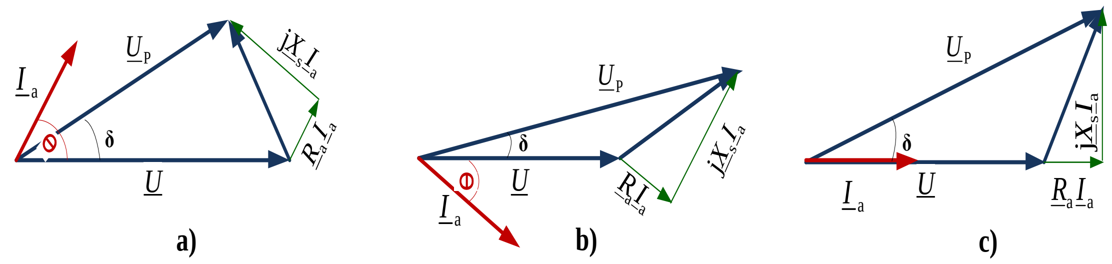

Fig 2.3 Synchronous generator phasor diagram a) leading power factor b) lagging power factor c) unity power factor

2.1.1.2 dq0 model

To achieve a simplified mathematical model which can expose synchronous generator performance under both steady state and transient conditions, it is best recommended to transform the abc equations of machine to a frame of reference with two axes dq which is fixed on the rotor magnetic axes, well known as Park's transformation and is introduced by

$$\boldsymbol{T}_{\mathrm{abc/dq0}} = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta - 2\Pi/3) & \cos(\theta + 2\Pi/3) \\ -\sin\theta & -\sin(\theta - 2\Pi/3) & -\sin(\theta + 2\Pi/3) \end{bmatrix} \tag{2.2}$$

Moreover, the direct axis in dq0 frame leads a axis in abc frame by the angle θ and both frames rotate with the same speed (rotor speed) counterclockwise generally in synchronous generator as seen in **Fig 2.4.**

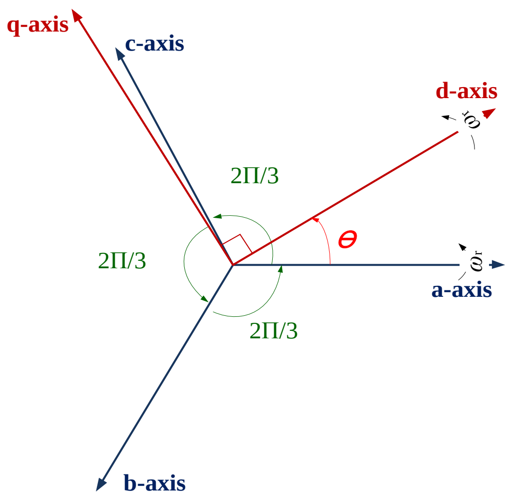

Fig 2.4 abc and dq0 frames axes comparison

Due to the transformation of parameters on the rotor reference frame, the time varying variables of machine will be omitted to simplify the state space modeling and further calculation of synchronous generator. The instance equivalent circuit of a two pole three phase synchronous generator in dq0 frame by consideration of one field winding and three short circuit windings as damper winding whose one of them is in the q and the rest are in the d axis direction is illustrated in **Fig 2.5**. The equivalent circuits are attained through generator's transformed equations from abc to dq0 frame which are called Park's equations. Park's equations' variables are represented in **Table 2.1** concisely.

It should be noted entire parameters are referred to stator windings. So, the view point is from stator and reference frame is fixed on rotor [7, 8].