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Reduction Reactive Power and Collapse Voltage Using Series Capacitors Compensation in Sudden Change Loads of Transmission Lines

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ABSTRACT

The continuous increase of disturbances on the interconnected electric power system resulting in its inability to reliably meet demands. This paper presents an application of a series capacitor compensation in transmission line and shunt reactors. Wherever all inductive loads required two kinds of power to operate with active power (P) and reactive power (Q) in design and operation of alternating current electric power systems. There is an important interrelation between reactive power and voltage of electrical power system which depends on losses compensation using series capacitors compensation. The reactive power losses in power system distribution can be reduced by connect series capacitors and shunt reactors with transmission lines. From noticing the location of reactive power control in distribution substation we can see the reactive power, series capacitors and shunt reactors, economical considerations which are effected on selection of using apparatus and equipments in power stations. Certain switching conditions of circuit breakers of electric power systems can result very high transient recovery voltages comparing with its normal conditions of working. Using Metal-oxide varistor (MOV) and shunt reactors helping on damping high voltages and return systems to its normal state. The paper describes how can we design and implement series capacitors compensation to solve problem working of reactive power and collapse voltage in transmission lines using simulation methods.

Keywords: Reactive power, Active power, Transient stability analysis, Transmission lines, Collapse voltage, Metal-oxide varistor (MOV).

تقليل القدرة المفاعلية وانهيار الفولتية باستخدام تعويض المتسعات المتوالية في حالة تغير الاحمال المفاجئة في خطوط النقل

الخلاصة

الزيادة المستمرة في اضطرابات نظام الطاقة الكهربائية المترابط (المتبادل التاثير) يؤدي الى عدم قابلية النظام لتلبية الاحمال المطلوبة بشكل موثوق. يقدم البحث الحالي تطبيقا لتعويض المتسعة المتوالية مع خط النقل وكذلك المتفاعلات المتوازية معها حيث ان جميع الاحمال الحثية تتطلب نوعين من القدرة اللازمة لتشغيلها مع القدرة الفعالة وكذلك القدرة المفاعلية في تصميم وعمل انظمة القدرة الكهربائية ذات التيار المتناوب علما ان هنالك علاقة مهمة بين القدرة المفاعلية وفولتية النظام الكهربائي المستند على تعويض الخسائر باستخدام تعويض متسعات التوالي. ان خسائر القدرة المفاعلية في انظمة توزيع الطاقة

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الكهربائية يمكن لها ان تقلل بربط متسعات التوالي والمتفاعلات المتوازية مع خطوط النقل ومن خـــلال ملاحظة موقع سيطرة القدرة المفاعلية في محطات التوزيع الثانوية يرى ان الجانب الاقتصـــادي يـــؤثر على هذه القدرة وكذلك على المتسعات المتوالية مع المتفاعلات المتوازية والتي بدورها تؤثر في عمليـــة اختيار الاجهزة والمعدات اللازمة في المحطات الكهربائية كما ان شروط فتح وغلق قواطع الدورة فـــي انظمة الطاقة الكهربائية يمكن لها ان تؤثر في اعادة فولتية عابرة ذات قيمة اعلى مـــن الحـــد الطبيعـــي لعملها لذا فان استخدام فجوة (MOV) والمفاعلات المتوازية يساهمان في امتصاص الفولتيـــات العاليـــة وارجاع النظام الى الحالة الطبيعية للعمل . يصف البحث الحالي كيفية تصميم وبناء متسعات التعـــويض المتوالية لحل المشاكل الناجمة عن القدرة المفاعلية وتذبذب الفولتية في خطوط النقـــل باســـتخدام طـــرق النمذجة .

INTRODUCTION

The increasing demand of electric energy and power quality constraints has given rise to a better use of transmission, sub-transmission, and distribution electrical power systems. This paper presents a detailed study on use of series capacitors compensation and shunt reactors to increase the capacity and flexibility of a transmission network. During the past two decades, the increase in electrical energy demand has presented higher requirements from the power industry. However, the most commonly used devices in present power grid are the mechanically-controlled circuit breakers. The long switching periods and discrete operation make them difficult to handle the frequently changed loads smoothly and damp out the transient oscillations quickly. In order to compensate these drawbacks, large operational margins and redundancies are maintained to protect the system from dynamic variation and recover from faults. [1, 2]

Therefore, investment is necessary for the studies into the security and stability of the power grid, as well as the improved control schemes of the transmission system. Different approaches such as reactive power compensation have been applied to increase the stability and the security of the power systems. The demands of lower power losses, faster response to system parameter change, and higher stability of system have stimulated the development of the Flexible AC Transmission systems (FACTS). Based on the success of research in power electronics switching devices and advanced control technology, FACTS has become the technology of choice in voltage control, reactive/active power flow control, transient and steady-state stabilization that improves the operation and functionality of existing power transmission and distribution system. [3, 4]

TRANSMISSION BASICS

In order to assess the voltage stability of a system, we introduce the simple radial system as in figure (1). Many voltage instability problems can be demonstrated with this system, since they are mostly locally met and originate from the inability of the system to meet the reactive power demand, which cannot be transported over long distances. Voltage instability phenomena which cover bigger parts of a power system are caused in a cascaded manner and the two bus system can easily be extended for studying larger grids. The system consists of a load fed from a voltage source E through a transmission line modeled as a series reactance, where the transmission line's resistance is neglected for simplicity reasons. The voltage at the load end is: [5, 6]

$$\bar{V} = \bar{E} - jX\bar{I} \qquad \text{......(1)}$$

Whereas, the complex power S transmitted over the line to the composite load is:

$$S = P + jQ = \bar{V}\bar{I}^* = \bar{V}\frac{\bar{E}^* - \bar{V}^*}{-jX} = \frac{j}{X}(EV\cos d + jEV\sin d - V^2) \qquad \text{........ (2)}$$

Thus, the active power can be written as:

$$P = \frac{EV}{X}\sin d \qquad \text{...... (3)}$$

And the reactive power is expressed as:

$$Q = \frac{EV}{X}\cos d - \frac{V^2}{X} \qquad \text{...... (4)}$$

The relationship of active and reactive power transmitted over a line indicate the relationship between active power and transmission angle and reactive power and voltage. Since our main focus is the voltage on the system buses, we eliminate the transmission angle δ (eq. 5):

$$(Q + \frac{V^2}{X})^2 + P^2 = (\frac{EV}{X})^2 \Rightarrow V^4 + V^2(2QX - E^2) + X^2(P^2 + Q^2) = 0 \qquad \text{...... (5)}$$

Equation (5) is a biquadratic equation with respect to the voltage (V) .The condition that has to be fulfilled in order to have at least one real solution is:

$$P^2 + Q\frac{E^2}{X} \le \frac{E^4}{4X^2} \qquad \text{......(6)}$$

Introducing the short- circuit complex power at the load bus in inequality (eq. 6) yields:

$$P^2 + QS_{sc} \le (\frac{S_{sc}}{2})^2 \qquad \text{....... (7)}$$

Inequality (eq. 7) gives the possible operational combinations of active and reactive power. Setting the active power (P) equal to (zero) corresponds to a purely inductive load. The maximum reactive power that can be transmitted over the line in steady-state operation is obtained and is equal to one fourth of the short-circuit power. Similarly, by setting the reactive power (Q) equal to (zero), representing a purely resistive load, the possible maximum active power transmitted over the line in steady state is obtained and equals to half of the short-circuit power. It can be inferred that it is harder to transport reactive than active power, while reactive power decreases the ability of the grid to transmit active power. Typically, the reactive power demand of loads varies significantly and is dependent of the nature of the loads and the degree of compensation. As a rule, loads are complex with a predominant inductive character and their power consumption can be written as: [7]

$$P + jQ = V^2G(1 + j\tan f) \qquad \ldots\ldots (8)$$

Thus, loads absorb reactive power and behave as inductances for a lagging power factor (tan φ > 0), while producing reactive power and behaving as capacitances for a leading power factor (tan φ < 0).

Assuming that power transmission is feasible, inequality (eq. 6) holds, the possible operating points are computed:

$$V^2 = \frac{E^2}{2} - QX \pm X\sqrt{\frac{E^4}{4X^2} - P^2 - Q\frac{E^2}{X}} \qquad \ldots\ldots(9)$$

The (eq. 9) represents a two dimensional surface in the (P, Q, V) plane as shown in figure (2) known as the onion surface [2]. The upper part corresponds to the plus sign and represents the actual operation of power systems, while the lower part corresponds to the minus sign. The equator of the surface is the locus of the maximum power that can be transmitted over the line with respect to the load’s power factor. The projection of the surface on the (P, V) plane generates the curves known as PV curves or nose curves figure (3), which depict the relationship between the active power transmitted and the bus voltage. The edge of the curves is the maximum active power that can be transmitted over the line and is considered as the voltage collapse point. A first interpretation of the nose curves is that for each load there are two operating conditions. However, normal operation is always on the upper part, while the lower part yields to abnormal operation. The multiple nose curves represent the different types of load and/or the degree of load compensation which yield a different power factor. The problem that rises from load compensation is that curves are shifted upwards, thus implying that the voltage collapse point can be near the normal operational voltage, making it, subsequently, hard to detect the proximity to voltage instability. The shaded area illustrates operation within the normal voltage range and stresses out that the high compensation of load can cause the voltage collapse point to lie within the span of nominal voltage operation. [8]

SYSTEM DISTURBANCE DUE TO LOADS INCREASE

Active and reactive power consumption of loads are both dependent on voltage and frequency variations. For voltage stability studies the characteristic curve of the loads on the PV and QV plane can be generally expressed as: [6]

$$P = P(V, z) \quad \ldots\ldots\ldots (10)$$
$$Q = Q(V, z) \quad \ldots\ldots\ldots (11)$$

Where (z) is a variable representing the load demand, which is directly associated with load increases or decreases. In figure (4) shows the PV curve of the system with two points.

A load with a constant active and reactive power consumption (load with a vertical characteristic in the PV diagram). As z increases, the characteristic of the load in the fig.4 is shifted to the right in a manner dependent on the load behavior figure (5). The intersection points of the nose curve and the load curve are the respective operation points of each load demand. However, as load continues to increase, there is a point where the load characteristic becomes tangent to the nose curve. That is considered to be the collapse point, and any further increase in load demand results in the lack of an intersection point between the two curves, which means that there is no feasible operating solution. [9]

System disturbance when that occurs in the transmission system such as a loss of a transmission line or loss of a generating unit, the grid's nose curve will be shrinking as shown in figure (6), since it is not any more capable of the same degree of power generation or transfer. At the same time, however, loads tend to maintain or restore their initial power consumption. The possible outcome is that an equilibrium, (intersection, between the two characteristics does not any longer exist and the system is driven to voltage instability). [5, 10]

SERIES COMPENSATION (SERIES CAPACITOR)

A schematic implementation of the series capacitor installation is shown in figure (7). The performance under normal and fault conditions should be considered. Under fault conditions, the voltage across the capacitor rises, and unlike a shunt capacitor, a series capacitor experiences many times its rated voltage due to fault currents. A metal-oxide varistor (MOV) in parallel with the capacitor may be adequate to limit this voltage. Thus, in some applications the varistor will reinsert the bank immediately on termination of a fault. For locations with high fault currents a parallel fast acting triggered gap is introduced which operates for more severe faults. When the spark gap triggers it is followed by closure of the bypass breaker. [11]

Immediately after the fault is cleared, to realize the beneficial effect of series capacitor on stability, it should be reinserted quickly, and the main gap is made self-extinguishing. A high-speed reinsertion scheme can reinsert the series capacitors in a few cycles. The bypass switch must close at voltages in excess of nominal, but not at levels too low to initiate main gap spark-over. [8, 10]

The discharge reactor limits the magnitude and frequency of the current through the capacitor when the gap sparks over. This prevents damage to the capacitors and fuses. A series capacitor must be capable of carrying the full line current. Its reactive power rating is (I^2 X_c per phase) and, thus, the reactive power output varies with the load current. The series compensation affects the transient stability limit of a power system. This limit is necessary to maintain all the generating units in synchronism when a disturbance occurs. The system response of these disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables. If the resulting angular separation between the machines in the system remains within certain bounds, the system maintains synchronism. Loss of synchronism, if it occurs, will usually be evident 2 to 3 seconds of the initial disturbance. Although the transient stability must be evaluated through detailed simulation, the equal area criterion could be used to evaluate the dynamic performance of a power system in response to fault conditions. The figure (8) shows the power – angle curve for the system with and without compensation (assuming 50% of degree of compensation). The area between the load power (P – load) and the power – angle curve is a measure of the transient stability. As shown in the figure, the area with compensation is greater than the area without compensation, which indicates an enhancement in the transient stability performance of the system. [10, 11]

THE RESEARCH POWER SYSTEM MODEL

This paper is describes and illustrates the modeling of series compensation and related phenomena such as subsynchronous resonance in a transmission system.

The single-line diagram shown in figure (9) represents a three-phase, (50 Hz), (735 kV) power system transmitting power from a power plant (2100 MVA) generators to an equivalent system through a (400 km) transmission line. The transmission line is split into two (200 km) lines connected between buses B1, B2, and B3.

To increase the transmission capacity, each line is series compensated by capacitors representing (40%) of the line reactance. Both lines are also shunt compensated by a (300 Mvar) shunt reactance. The shunt and series compensation equipment is located at the B2 substation where a (300 MVA-735/230 kV) transformer feeds a (230 kV-200 MW) load.

Each series compensation bank is protected by metal-oxide varistors (MOV1 and MOV2). The two circuit breakers of line 1 are shown as CB1 and CB2. This power system is available in the three-phase power model. The generators are simulated with a simplified synchronous machine block. Two transformers three-Phase (two windings) block are used in model. Saturation is implemented on the transformer connected at bus B2. The B1, B2 & B3 blocks are three Phase V-I Measurement blocks taken from the Measurements library. The output faults are programmed to output voltages in (p.u) and currents in (pu/100 MVA).

SIMULATION AND CALCULATION OF SERIES COMPENSATION

The series compensation subsystem of the power system model in figure (10.A), consists three-phase module which consists of three identical subsystems, one for each phase. The capacitance value and the MOV protection level are calculated. The model shows the details of the connections of the series capacitor and the Surge Arrester block (which MOV in figure (10.B). The transmission line is 40% series compensated by a 136 μF capacitor. The capacitor is protected by the MOV block. Each MOV block consists of

60 columns with protection level reference corresponds to 2.5 times the nominal capacitor voltage which obtained at a nominal current of 2 kA RMS.

A gap is also connected in parallel with the MOV block. The gap is fired when the energy absorbed by the surge arrester exceeds a critical value of 30 MJ.

To limit the rate of rise of capacitor current when the gap is fired, a damping RL circuit is connected in series in fig.10.B. It shows in figure (10.C), how you calculate the energy dissipated in the MOV by integrating the power (product of the MOV voltage and current). When the energy exceeds the 30 MJ threshold, a closing order is sent to the Breaker block simulating the gap.

Three-phase series compensation module.

Total line reactance in positive-sequence: X_1 = 0.9337e-3*(2*pi*50)*200=58.6 Ω. Capacitance required for 40% compensation: Required series capacitance:

X_c=0.4*58.6 = 23.4 Ω or C_S= 136 µF.

MOV protection level required to protect the capacitors at (2.5) times the nominal capacitor voltage. (The nominal capacitor voltage is taken at 2 kA rms line current)

Vprot. = 2.5*2kA*23.4*sqrt (2)= 165.4 kV.

AN OVERVIEW OF SPECIFIC SCENARIOS RELATED TO THE NORMAL AND FAULTS OPERATIONS

A. SETTING THE INITIAL LOAD FLOW AND OBTAINING STEADY STATE

Before performing transient tests, we must initialize power system model for the desired load flow. This paper uses the load flow utility to obtain an active power flow of 1500 MW out of the machine with a terminal voltage of (1 p.u, 13.8 kV). The series compensation increasing the power transfer capability of transmission lines. Some steady state analyses are performed using Matlab Simulations ver 8. (R2009 a) [20]. Table (1) shows the results of these simulations. Practically in this paper the voltage is constant when using this type of compensation so we fixed this voltage on (1 p.u, 13.8 kV). The effectiveness of the series compensation improving the power transfer capability of the transmission line is demonstrated with this simple case.

B. TRANSIENT PERFORMANCE FOR FAULTS APPLIED ON MID LINE ONE (L1) IN POWER SYSTEM MODEL

To speed up the simulation we need the actual power system and the sample time (Ts=50e-6) also needed to initialize the functions of model properties. (Ts) is used in the discrete integrator block of the MOV energy calculator to control the gap. In figure (9) the fault is applied on mid line one (L1), in the line side of the capacitor bank with the three-phase blocks and the three-phase circuit breaker blocks CB1 and CB2. Faults are applied on mid L1 at (t = 0.02 s) then CB1& CB2 are initially closed then and opened at (t = 0.1 s), simulating a fault detection and opening time of (0.08s). The fault is eliminated at (t = 0.12 s), time (0.02 s) after the line opening.

SIMULATION RESULTS AND DISCUSSIONS

This paper presents and illustrates the modeling of series compensation modeling and simulations of the system using Matlab. Fault applied on mid line 1 in power system model to cases (3-phase to ground, line to ground, double line and double line to ground) as followed in figures from (11-42).

The results presents an attempt to design a simulations model to series compensation in transmission lines of power system which consist the analysis of the capacitor phenomena in both static and dynamic states:

A. STATIC ANALYSIS – LOAD ABILITY LIMIT

In order to compute the voltage stability limit. Line capacities, generator capabilities and voltage-dependent load characteristics considered, so an estimation of the voltage stability limit is obtained, when the operation point in the proximity of the voltage collapse point which yield to divergence of the load flow to its place.

B. DYNAMIC ANALYSIS

For the dynamic analysis the system model is adjusted to include load, generators and compensation devices dynamics. The system is subjected to credible disturbances and the system's behavior is simulated by solving the respective differential equations.

The ultimate goal is to detect the most critical disturbances, the determining dynamic factors which lead to voltage instability and the response of the system to them. Despite the great potential of series capacitors compensation improving the steady state and the dynamic performance of the system, in presence of line faults, severe over voltages and large transient recovery voltages are produced due to the trapped charge in series capacitors after the switching operations. The simulation starts in steady state at t = 0.02 s, the simulation applied for all types of faults (L-G, LL-G, LL, LLL-G). These faults are applied on mid Line one (L1). Fault current reaches more than 10 kA figure (15) when three-phase to ground fault (LLL-G) applied. During each fault, the MOV conducts at time (0.03 s) figure (17) and the energy dissipated reached to 2.5 MJ time between (0.03-0.07 s) figure (18). Also the maximum energy does not exceed the 30 MJ threshold level and the gap is not fired (the energy stays constant at 2.5 MJ. figure (18)). The current reaches to zero in bus-bar 2 (basic power =100 MVA) when protection relays are open which yield to open CB1 and CB2 at t=0.1 s figure (14). The series capacitor stops discharging and its voltage oscillate around 150 kV figure (16). Fault currents reached to (8 kA, 10 kA and 10 kA) when line to ground fault (L-G), double line fault (LL) and double line to ground fault (LL-G) are applied figure (23, 31, 39). The series capacitor stops discharging and its voltage oscillate around 150 kV figure (24, 32, 40). The energy dissipated in the MOV faster in figure (34) than in figure (18, 26, 42). Final consultation on this paper that the series compensation for the given system, 40% series compensation increases the power flow through the lines considerably and reduces the angular separation between the sending ends and receiving end within the acceptable limits.

CONCLUSIONS

In this paper the basic structure of SVC operating under typical bus voltage control and its model are described. The model is based on representing the controller as a transmission line of 40% series compensated by a 136 μF capacitor and shunt reactance of 300 Mvar which provide the fast acting support voltages that prevent the possibility of voltage reduction and voltage collapse at the bus that use in the research model. In this paper SVC is proposed for improving in damping of oscillations and transient stability of the two-area power system. The proposed controller is used SVC under abnormal system condition. The simulation results have shown that the selected SVC are capable of providing sufficient damping to the system oscillation and improving the steady state and transient voltages performance over a wide range of operating conditions and various types of disturbances (faults of three phase to ground fault - single line to ground fault – double line fault, and finally the double line to ground fault). The goal of providing voltages, reactive power support and improving the damping of system oscillations are achieved by using suitable design of SVC controller so which used in this research.

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Tab (1) Load flow machine in steady state case with series compensation .

Machine	2100 MVA	13.8 kV
Nominal	2100 MVA	13.8 kV rms
Van phase	5.95°	-
V_{ab}	13.8 kVrms [1pu]	35.95°
V_{bc}	13.8 kVrms [1pu]	-84.05°
V_{ca}	13.8 kVrms [1pu]	155.95°
I_a	63.060 kArms [0.7178 pu]	-0.10°
I_b	63.060 kArms [0.7178 pu]	-120.10°
I_c	63.060 kArms [0.7178 pu]	119.90°
P	1498.9 MW [0.7138 pu]	-
Q	158.76 MVars [0.0756 pu]	-
P_{mec}	1514.8 MW [0.7213 pu]	-
Torque	9.6434 MN.m [0.7213 pu]	-

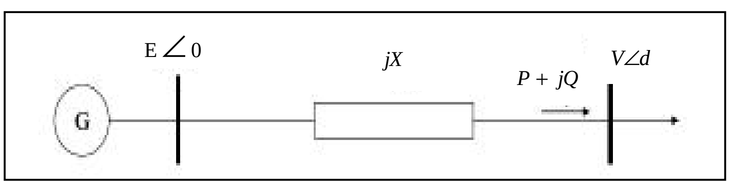

Figure (1) Single line diagram of a two bus system

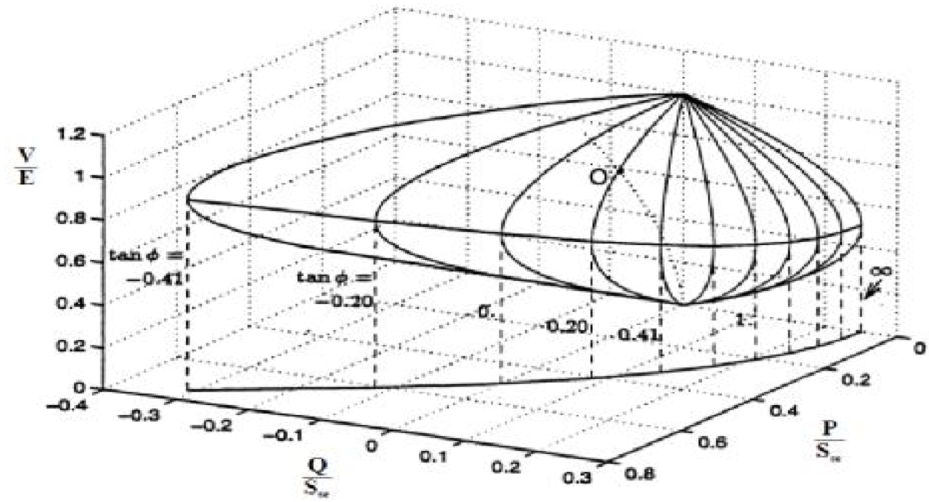

Figure (2) Voltage with respect to load active and reactive power in normalized quantities. [3]

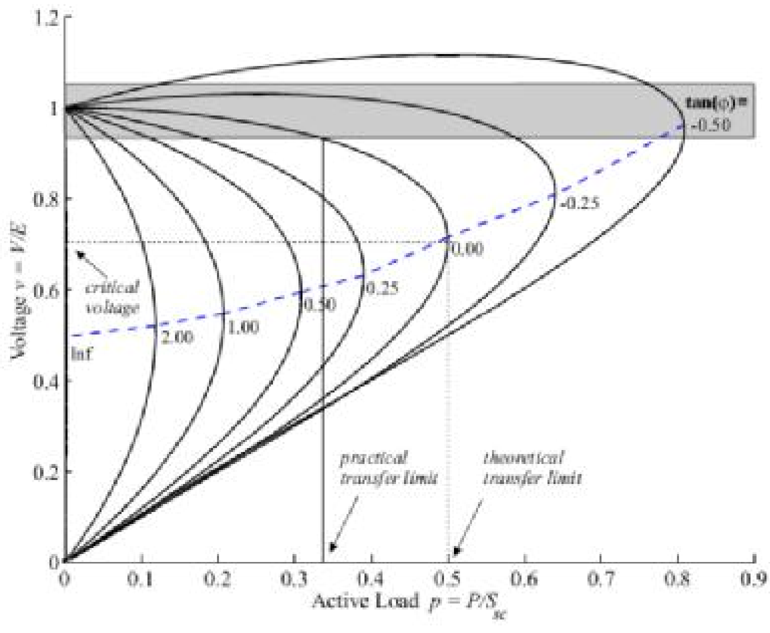

Figure (3) The PV or nose curves. [6]

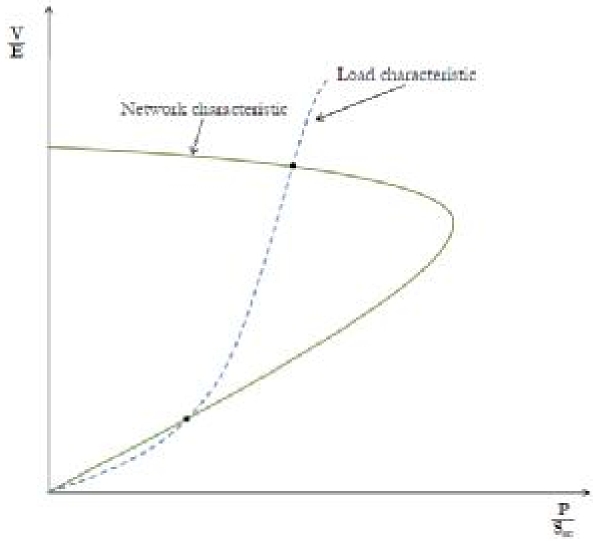

Figure (4) PV diagram of network and load

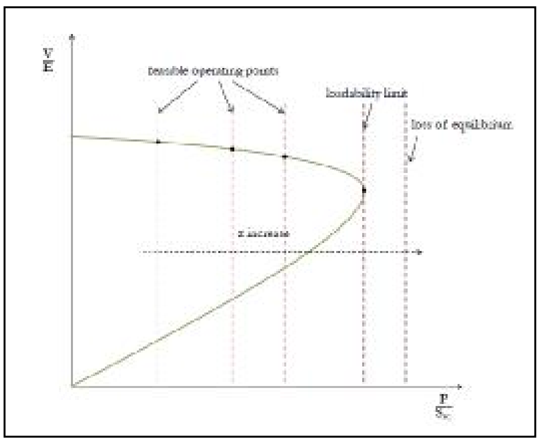

Figure (5) Gradual increase in the system load.

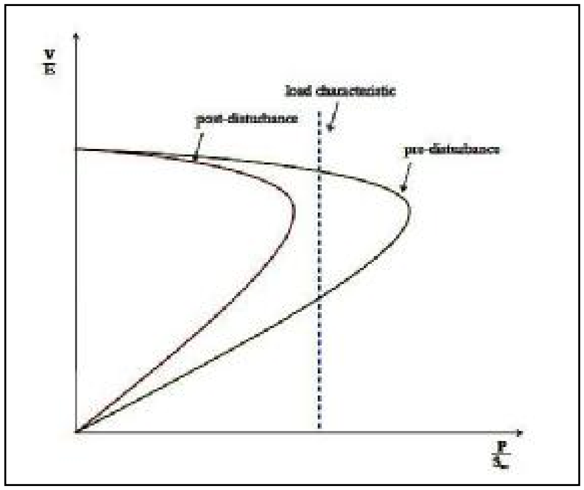

Figure (6) Shrinking of the "nose" curve due to system disturbance.[3]

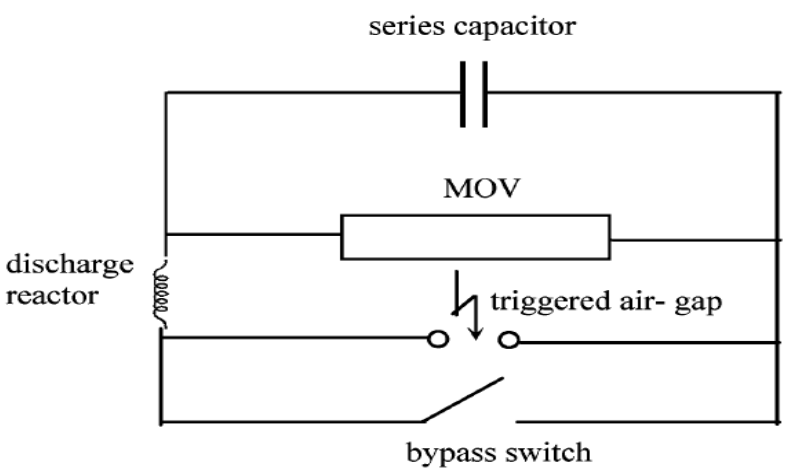

Figure (7) Schematic diagram of a series capacitor installation

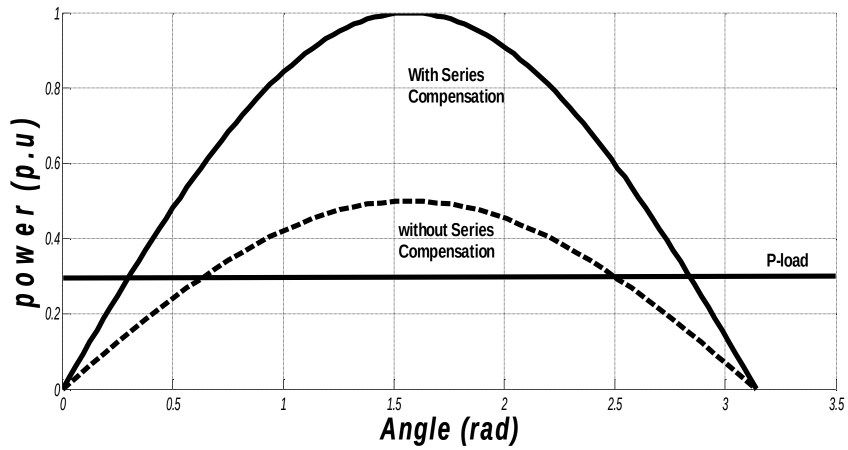

Figure (8) Power angle plot comparison with/without series compensation

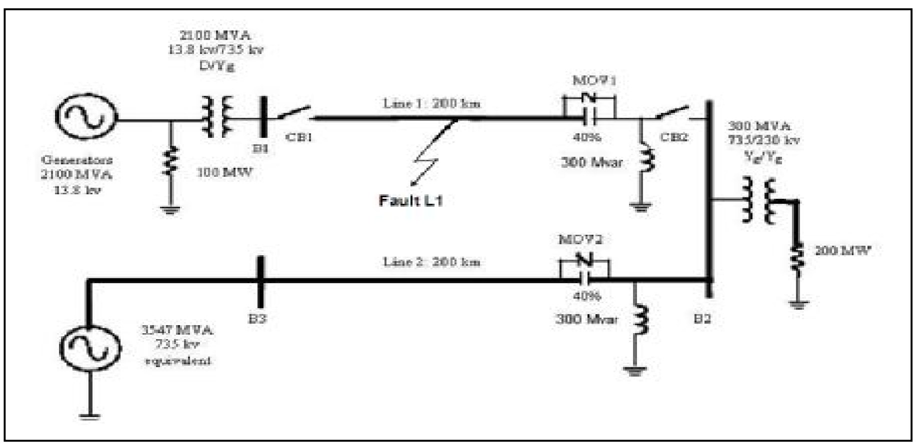

Figure (9) The single-line diagram with series and shunt compensated transmission line system used in this research

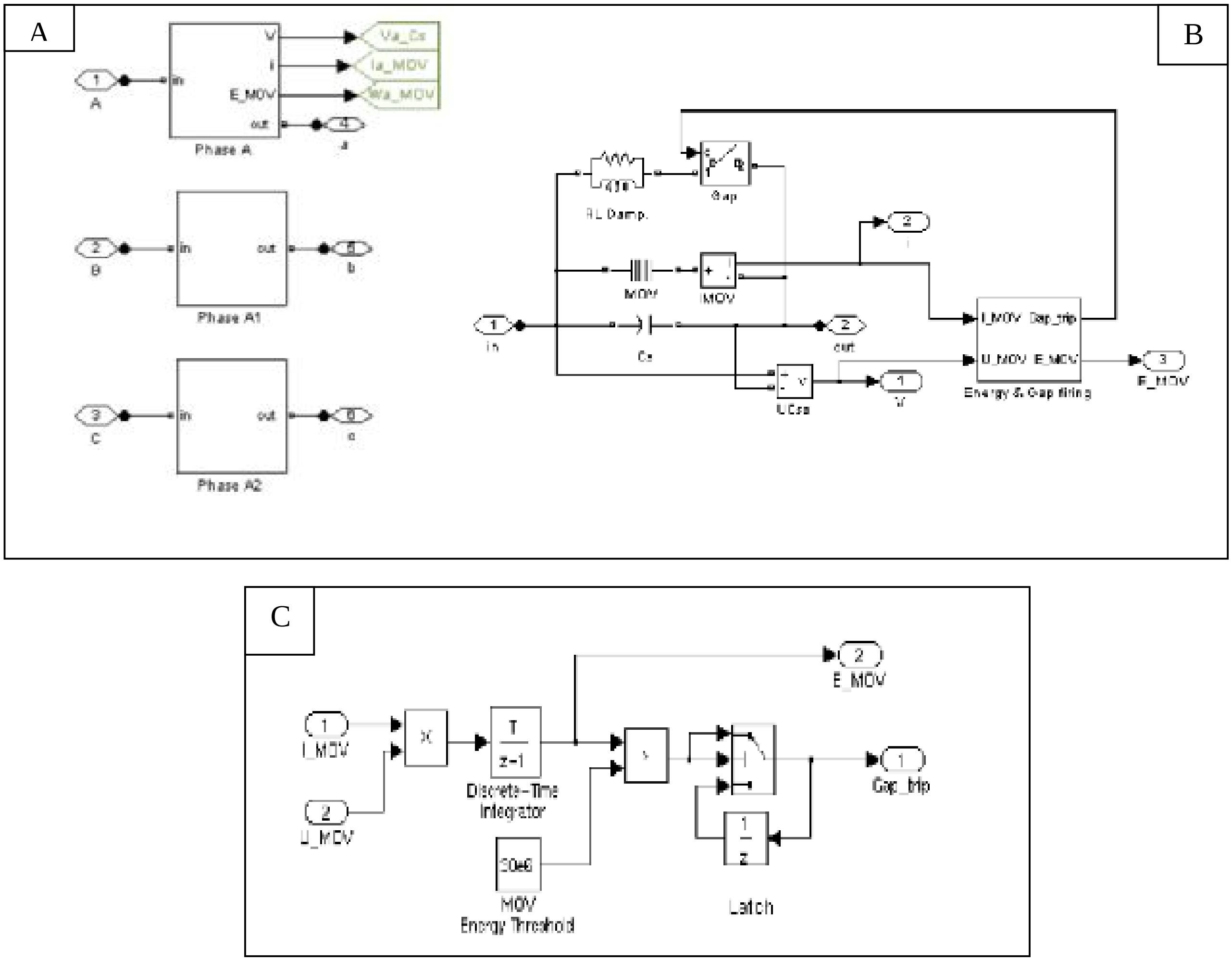

Figure (10) A. Series Compensation Module, B. Series Compensation1/ Phase A Subsystem, C. Series Compensatin1/ Phase A Subsystem/Energy and Gap Firing

A. Three-Phase-to-Ground Fault applied on mid Line one (L1) in power system model:

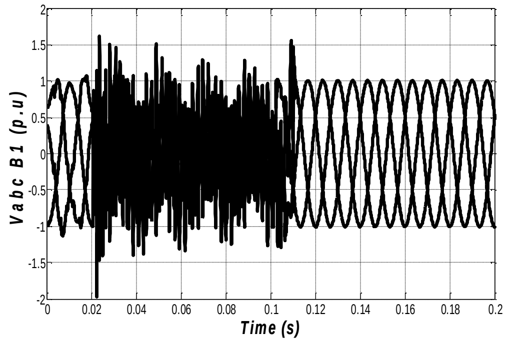

Figure (11) A-3-phase measured voltage at the bus-bar 1(an "A-B-C" 3-phase-to-ground fault occurring at fault locations).

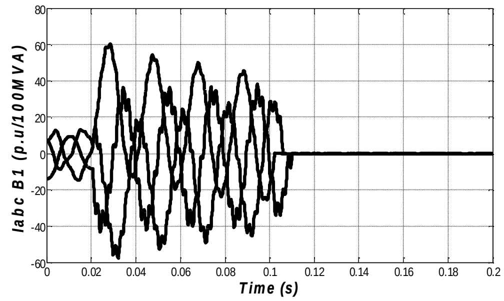

Figure (12) A-3-phase measured current at the bus-bar 1 (an "A-B-C" 3-phase-to-ground fault occurring at fault locations).

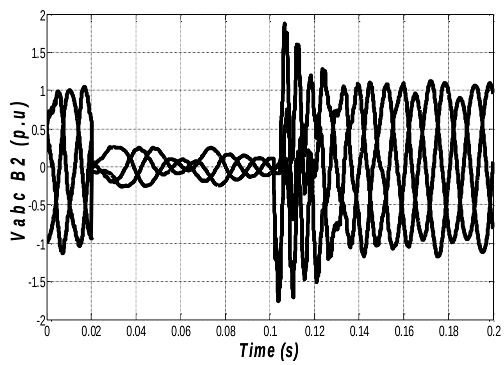

Figure (13) A-3-phase measured voltage at the bus-bar 2(an "A-B-C" 3-phase-to-ground fault occurring at fault locations).

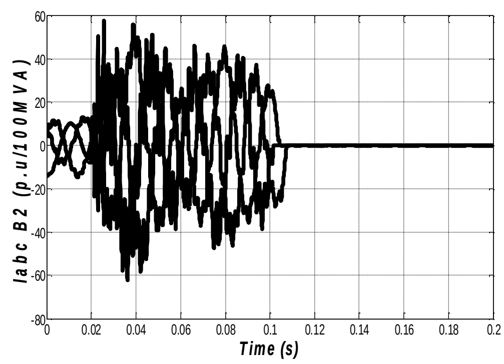

Figure (14) A-3-phase measured current at the bus-bar 2 (an "A-B-C" 3-phase-to-ground fault occurring at fault locations).

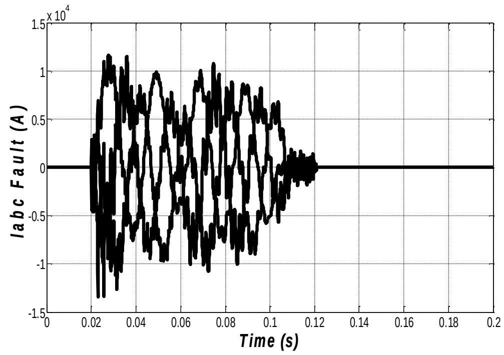

Figure (15) "A-B-C"-3-phase measured current fault on line 1.

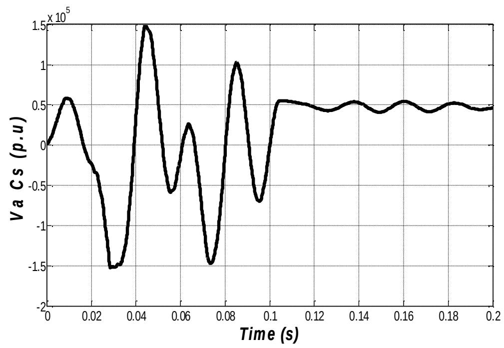

Figure (16) "A-phase voltage across the capacitor (an "A-B-C" 3-phase-to-ground fault).

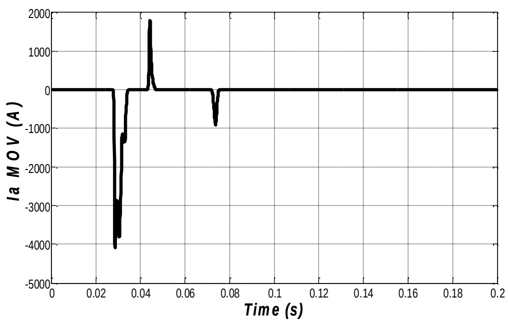

Figure (17) A-phase currents across the MOV and capacitor (an "A-B-C" 3-phase-to ground fault).

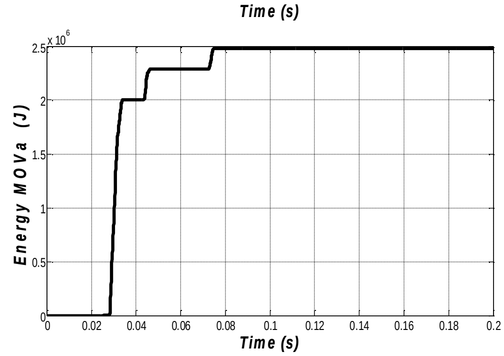

Figure (18) The energy dissipated in the MOV during the 3-phase-to ground fault.

B. Line-to-Ground Fault applied on mid Line one (L1) in power system model:

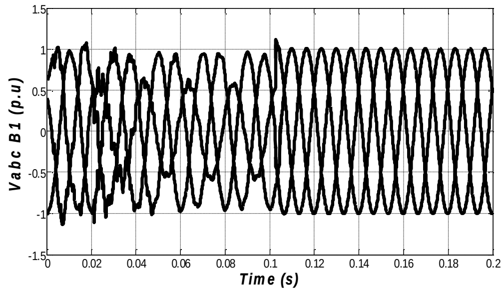

Figure (19) A-3-phase measured voltage at the bus-bar 1(an "A" phase-to-ground fault occurring at fault locations).

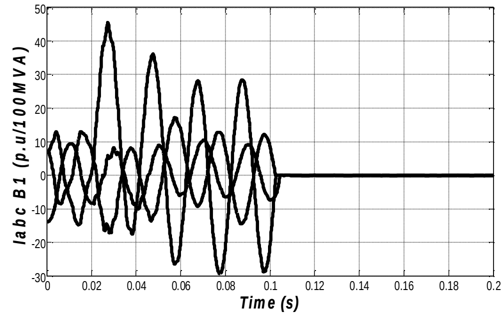

Figure (20) A-3-phase measured current at the bus-bar 1 (an "A" phase-to-ground fault occurring at fault locations).

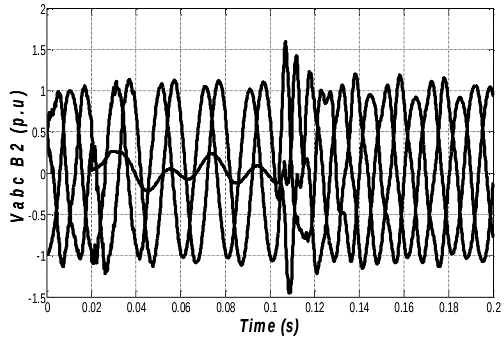

Figure (21) A-3-phase measured voltage at the bus-bar 2 (an "A" phase-to-ground fault occurring at fault locations).

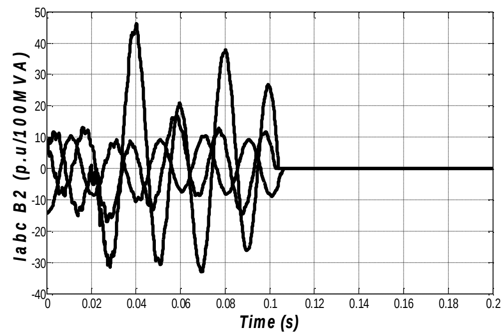

Figure (22) A-3-phase measured current at the bus-bar 2 (an "A" phase-to-ground fault occurring at fault locations).

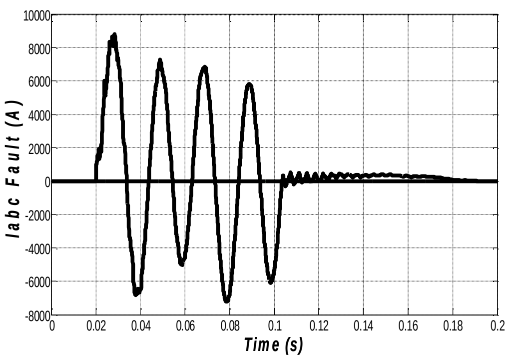

Figure (23) A-3-phase measured current fault on line 1 (an "A" phase-to-ground fault)

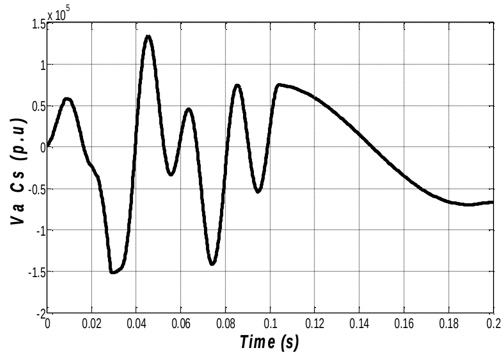

Figure (24) A-phase voltage across the capacitor (an "A" line-to-ground fault).

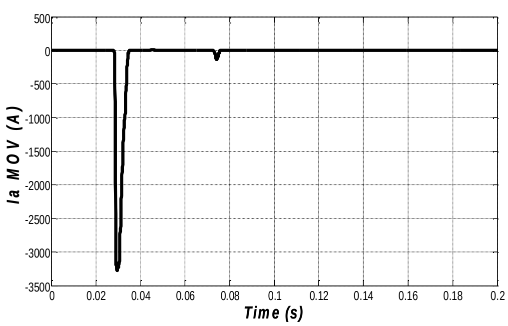

Figure (25) A-phase currents across the MOV and capacitor (an "A" line-to ground fault).

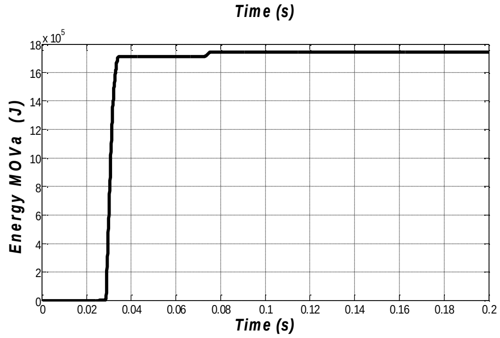

Figure (26) The energy dissipated in the MOV during the line-to ground fault.

C. Double line Fault applied on mid Line one (L1) in power system model:

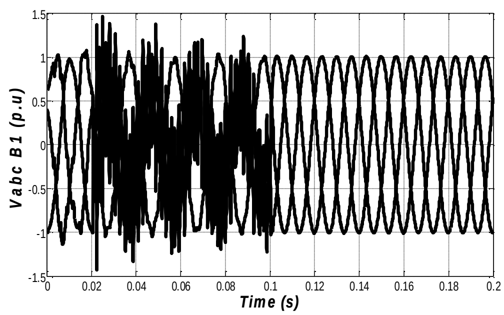

Figure (27) A-3-phase measured voltage at the bus-bar 1 (an "A-B" Double line fault occurring at fault locations).

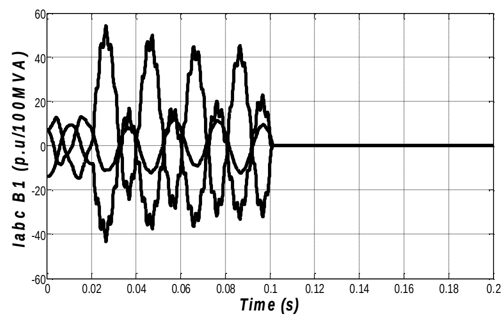

Figure (28) A-3-phase measured current at the bus-bar 1 (an "A-B" Double line fault occurring at fault locations).

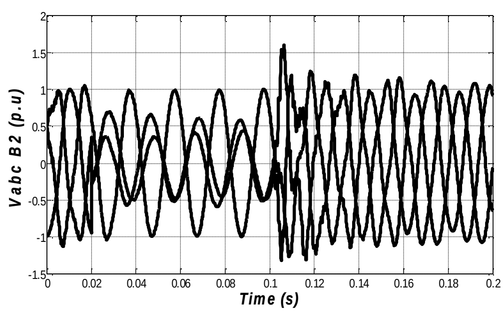

Figure (29) A-3-phase measured voltage at the bus-bar 2 (an "A-B" Double line fault occurring at fault locations).

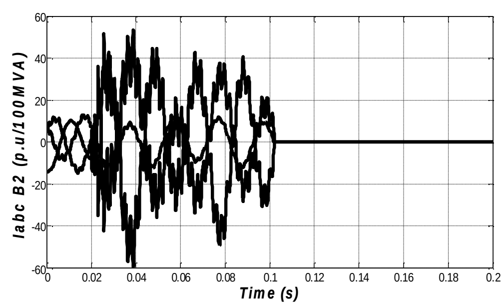

Figure (30) A-3-phase measured current at the bus-bar 2 (an "A-B" Double line fault occurring at fault locations).

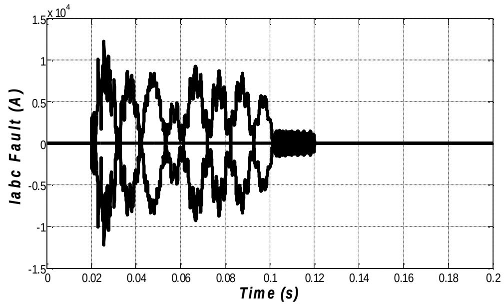

Figure (31) A-3-phase measured current fault on line 1(an "A-B" Double line fault)

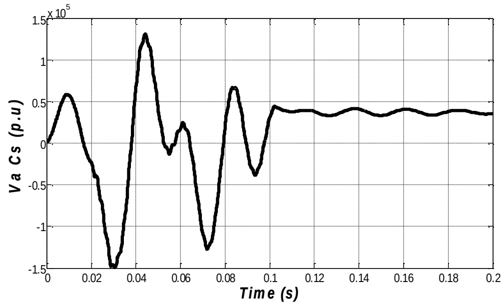

Figure (32) A-phase voltage across the capacitor (an "A-B" Double line fault).

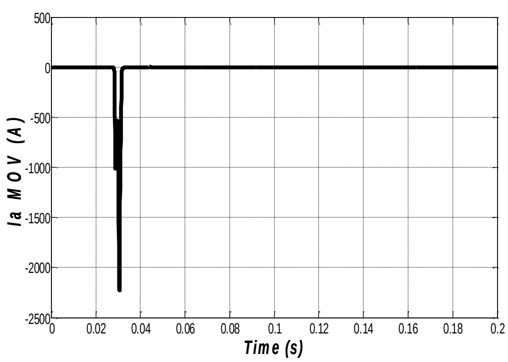

Figure (33) A-phase currents across the MOV and capacitor (an "A-B" Double line fault).

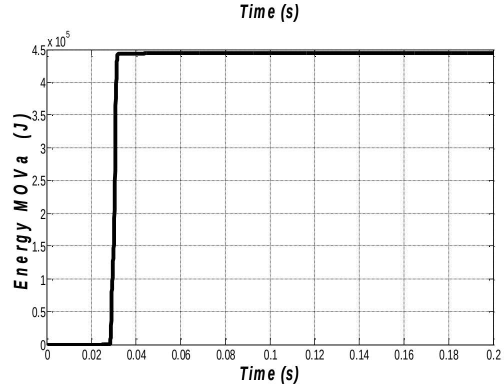

Figure (34) The energy dissipated in the MOV during the Double line fault.

D. Double line to ground Fault applied on mid Line one (L1) in power system model:

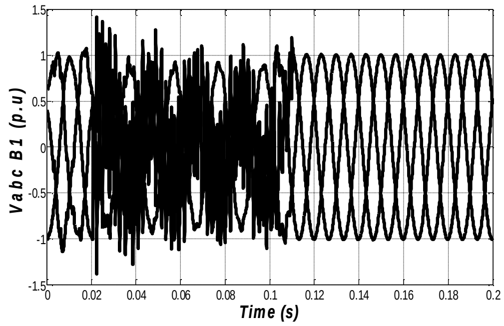

Figure (35) A-3-phase measured voltage at the bus-bar 1 (an "A-B" Double line to ground fault occurring at fault locations).

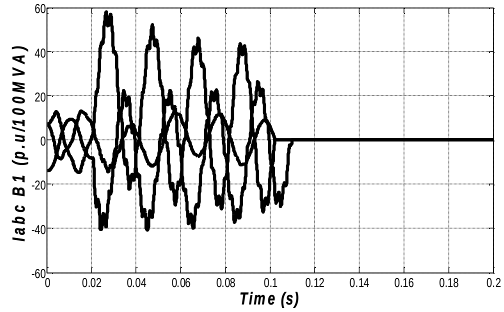

Figure (36) A-3-phase measured current at the bus-bar 1 (an "A-B" Double line to ground fault occurring at fault locations).

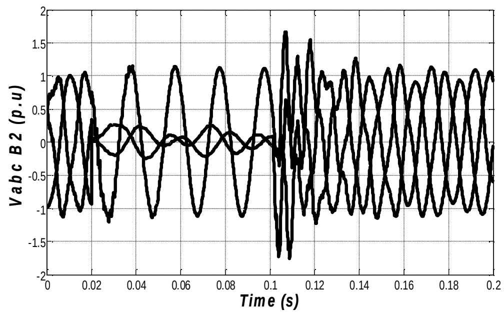

Figure (37) A-3-phase measured voltage at the bus-bar 2 (an "A-B" Double line to ground fault occurring at fault locations).

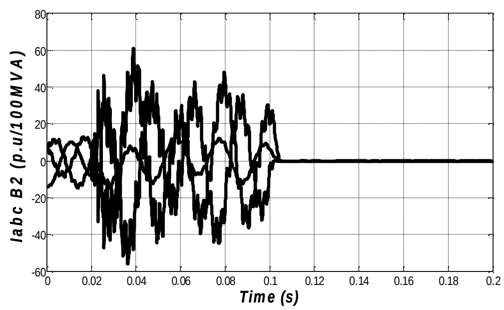

Figure (38) A-3-phase measured current at the bus-bar 1 (an "A-B" Double line to ground fault occurring at fault locations).

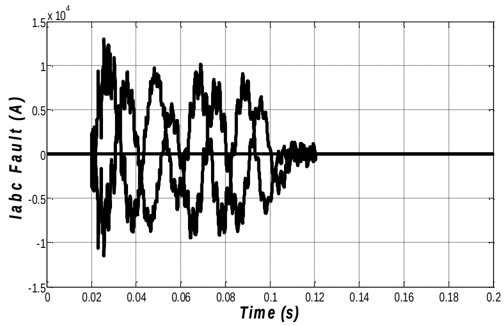

Figure (39) A-3-phase measured current fault on line 1(an "A-B" Double line to ground fault).

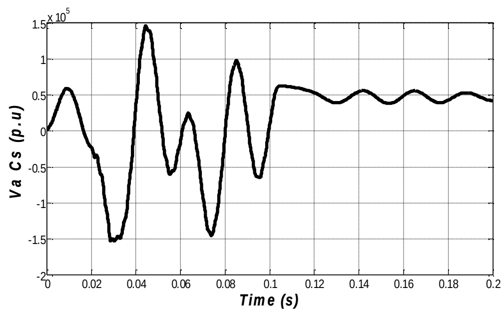

Figure (40) A-phase voltage across the capacitor (an "A-B" Double line-to-ground fault).

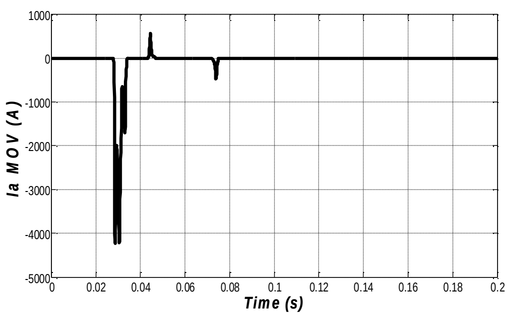

Figure (41) A-phase currents across the MOV and capacitor (an "A-B" Double line-to ground fault).

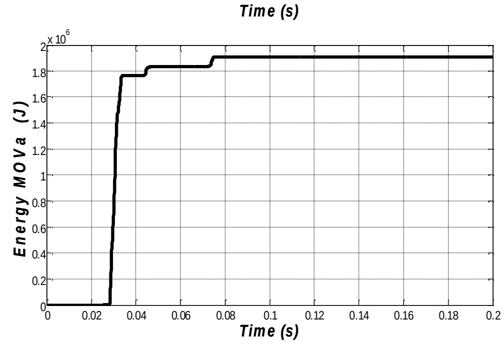

Figure (42) The energy dissipated in the MOV during the Double line-to ground fault.