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The Impacts of Integrated Metallic Oxide Varistor (MOV)-Capacitor Banks on High Voltage AC Power Transmission System

Oluwaseun Olanrewaju Akinte[1] Boonrit Prasartkaew[2] Taiwo Samuel Aina[3]

[1]*Department of Energy and Materials Engineering, Rajamangala University of Technology, Thanyaburi, Pathum Thani 12110, Thailand*

[2]*Department of Energy and Materials Engineering, Rajamangala University of Technology, Thanyaburi, Pathum Thani 12110, Thailand*

[3]*Department of computer science and Technology, University of Bedfordshire, Vicarage St, Luton, LU1 3JU, United Kingdom*

[*]*Corresponding Email:* oluwaseun_o@mail.rmutt.ac.th

Abstract

To maximize the efficient utilization of HVAC (high voltage alternating current) system of power transmission in terms of power efficiency improvement, voltage support, sudden shift in loadings, occurrence of transient, power regeneration and regenerative braking currents (harmonics), the need for installation of integrated metallic oxide varistor-electrochemical capacitor banks is essential in electrical power systems because the application of electronic converters (rectifiers, inverters, bi-directional converters) are responsible for regenerative braking currents (harmonics) continuously. Hence the behavioural response from an external disturbance on electrical power system should be taken seriously into consideration if continuous effective power flow must be maintained under certain conditions within the integrated system. This paper presents a non-compensational and compensational three-phase HVAC power transmission system, its transient effects during asymmetric faults (line-ground, line-line). Investigation of integrated metallic oxide varistor (MOV)-series compensational (electrochemical capacitors) effect on HVAC power system was carried out showing the power flow analysis between the power generation source and the load demand containing the modelled non-series and series compensated HVAC power transmission system in response to its behaviour through the application of MATLAB, Simulink and Simscape power system tool software.

Keywords: *High Voltage AC Power System, Metallic Oxide Varistor (MOV), Electrochemical Capacitor, Transient Effect-Line fault and Series Compensation.*

1.0 Introduction

Electrical power equipment uses active power for the performance of electrical heater, energization, power flow motion and lighting. Non-linear loads (inductive devices) like choker circuit, compressors, and electromagnetic device (transformer) need reactive power to produce magnetic flux in operation. The reactive power, Q does not perform any working operation. Active (P) and reactive (Q) powers are developed from electric power systems. The reactive power (Q) generated from non-linear loads emanate from commercial and industrial loads. However, power system's quality is clean in consideration, but the clean power can undergo conversion into a dirty power when electric current or voltage (basic electrical quantities) deviate from its ideal behaviour leading to imbalance in phase and frequency between the voltage and current. Unplanned events arising from power interruption in the whole part, or some portion of an electrical power system known as 'black start' threatens the system's stability identified as a disturbance or interruption. The causes of this disturbance are transient, root mean square and steady state disturbances which lead to sagging of voltage, power outage, regenerative braking currents (harmonics), voltage flickering, over voltage/under voltage and transients. They possess a negative effect on the power system stability such as electronic chips damage, overheating/motor stalling, excessive losses/equipment shutdown, short lifespan of lightning filaments/short lifespan of winding conductors, trip relay/blown fuse and light flickering.

There are practical methods of improving the power system's stability such as increment in the number of parallel lines application, generator reduction, shunt/series compensation and transformer reactance which can also improve the system's power factor [2]. The integrated MOV-capacitor will provide reactive current generation for the compensation of reactive power consumption by the induction loads thereby improving the power factor between the load demand and utility grid. The installation of metallic oxide varistor-capacitor circuit at the load ending (panel boards of the distribution) will reduce losses at the power distribution grid. In general, most of the electrical power systems operate at a 50Hz-60Hz frequency range as designed, where some non-linear loads (induction loads) produce multiples of the fundamental range of frequency (50Hz-60Hz) with their respective voltages/currents known as higher frequencies ($2F_O$, $3F_O$, $4F_O$, $5F_O$, etc) called harmonics where F_O = 50Hz or 60Hz. Generation of harmonics can flow from the utility grid to enter the power plant through a non-linear source of another neighbouring power plants or can be within the power plant production itself. The metallic oxide varistor (MOV) shields the capacitor banks by reducing the rate of current rise in the capacitor during gap fire [1] thereby acting as a surge protection to avoid overheating and prevention of damage to the capacitor banks.

2.1 HVAC System of Transmission

The high voltage AC system of power transmission is classified into 2 parts majorly, which are:

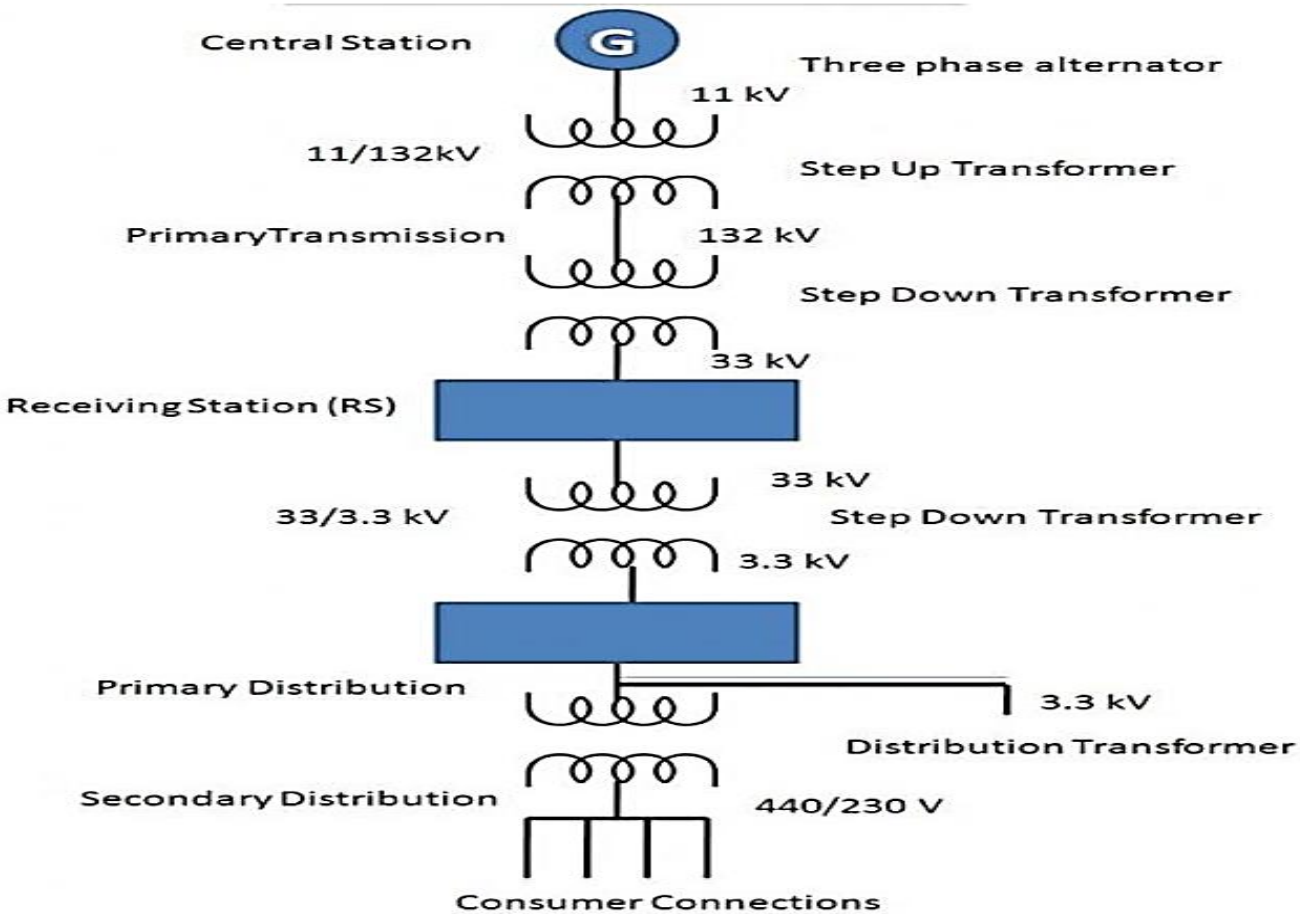
A. AC system of transmission
B. AC system of distribution

The individual transmission and distribution part of the AC above is further sub-divided into another two components namely:

C. System of primary AC transmission
D. System of secondary AC transmission

At present, generation of power, transmission of power and transmission of secondary AC are 3-phase AC system but the distribution system to the consumer unit may be a three phase or single-phase (1-phase) depending on the requirement of the consumer unit.

Figure 1: High Voltage AC Transmission System [3]



2.1.1 AC Primary Transmission

The figure 1 above consist of central station that generate AC power from a three-phase (3-phase) alternator at a voltage rating of 6.60KV/11.00KV/13.20KV/32.00KV. A regulating device (3-phase transformer) steps up the voltage rating to 132.0KV. the high voltage AC transmission requires smaller cross-sectional area of conductors. High voltage AC power transmission reduce line losses with improvement in the efficiency, the three-phase-three wire overhead high voltage AC power transmission line is being terminated at the step-down regulator (transformer) in a receiver's station. The receiving station's location is outside the city for the reason of safety while the voltage rating is stepped down from 132.0KV to 33.0KV.

2.1.2 AC Secondary Transmission

Power transmission rating is at 33.0KV in the AC secondary transmission from the receiver's station through cables (underground connection) at various positions (locations) of the city. The voltage rating is further reduced from 33.0KV to 3.30KV at the substation from the stepdown regulator (transformer).

2.1.3 AC Primary Distribution

The output voltage rating of 3.30KV of the substation can be distributed directly to the consumer if the load demand exceeds the apparent power rating of 50KVA with special feeders' application called AC primary distribution system.

2.1.4 AC Secondary Distribution

The voltage rating level is being reduced from 3.30KV to 440V/230V (line-line/line-neutral) by a stepdown transformer at the AC distribution substations. The three phase-three wire system (440V/230V) is the most common AC secondary distribution system. The single phase (230V) residential load is a connection between a line and the neutral while the three phase (440V) involve connecting directly across the phase lines to the load motor. The AC frequency of operation in the United Kingdom (UK) and India is 50Hz, while in the United State of America is 60Hz as a standard design. Single phase traction systems utilize lower frequencies of operation (16.67Hz or 25Hz) as their application [4].

2.2 Classification of AC Transmission Line

The three constant parameters of an AC transmission line are the resistors, inductors, and capacitors circuits which are distributed constantly through the whole lengthy line. The circuit series impedance contains the resistor and inductor, the capacitance from a conductor's existence to the neutral in a 3-phase line provides a shunt path across the line's length entirely. Capacitance effect causes calculation complications in the line of transmission depending on the accounted capacitance of the capacitor's approach. The overhead AC transmission lines are classified into:

i. **AC Short Line of Transmission**

AC short line of transmission has a low comparative line voltage less than 20KV with 50Km overhead transmission line length. Capacitance effect is low which can be neglected because of lower voltage and smaller length. During the study performance of an AC short transmission line, the line's resistance and inductance are considered.

ii. **AC Medium Transmission Line**

The AC medium transmission line has a moderately high line voltage rating above 20KV and less than 100KV with 50Km to 150Km range of overhead transmission line length. The capacitance effect in consideration is due to the voltage rating of the line and sufficiency in length. The capacitance line's distribution is divided into condenser form in parts and lumped which is shunt across the line beyond one point for calculation purposes.

iii. AC Long Transmission Line

The AC long transmission line has a very high line voltage rating of 100KV and 150Km above overhead transmission line length. In dealing with this type of line, uniform distribution of line constants must be considered over the line length entirely and imploring rigorous method solution [4].

2.3.0 Power Transfer Potentials of High Voltage AC System

The surge impedance, Z limits the power transfer potential of high voltage alternating current (HVAC). Alternating current line produces and consumes reactive power when reactive power generated on load production equals to the generated reactive power on load consumption, then natural loading is the result. Equation (1) below expresses the natural load on an alternating current line [12]:

Surge impedance loading, $SIL = (V_o^2)/Z_s$.. (1)

Where V_o = Operational voltage, Z_s = Surge impedance.

Reactive power production and consumption by alternating current (AC) lines create serious issue, if the capacitance in parallel connection (shunt capacitance) measured in farads/unit length, inductance in series measured in henry/unit length, operating voltage measured in volts and operating current measured in amperes (A) of an overhead alternating current line, then the reactive power on the production and consumption of load by the alternating current line is defined mathematically as:

$Qc = w * c * v^2$.. (2)

$QL = w * L * I^2$……………………………………………………………...... (3)

Surge impedance occurs when Qc = QL

$W * c * v^2 = w * L * I^2$……………………………………………………………… (4)

$V/I = (L/c)^{1/2} = Z_s$……………………………………………………………… (5)

The natural power line limitation is expressed mathematically as:

$P_n = IV = I * (IZ_s) = I^2 Z_s = V_o^2/Z_s$ ………………………………………….... (6)

The maximum power flow equation in high voltage AC line limitation is expressed mathematically below:

$P = \frac{Vt*E}{X} \sin(\delta)$……………………………………………………………… (7)

The load angle, δ, of 90^0 gives the maximum steady state power limitation value:

$P_e = \frac{Vtn*En}{Xr}$, V_{tn} = load terminal voltage (Volts), E_n = Internal generator emf (Volts), X_r = line reactance in (ohm). Generally, the operational angle in high voltage AC lines is below 30^0 because of relays in synchronism. The power transfer potential increment from (150-250) % of limitation in natural load may occur through the extensive application of capacitors in series arrangement [13].

2.3 Ultra-capacitor or Super capacitor (UC or SC) Storage System

Capacitors are in 3 categories, namely: electrochemical, electrostatic, and electrolytic capacitors. The store energy in form of electric charges and release electrical energy through chemical processing. UC/SC are known as electrochemical capacitors, operating on electric double layer principle [9, 10]. They are interface-constructed charge separation between solid electrodes and electrolyte. The electrode materials attract ions to form UC/SC in the electrolyte (electric double layer processing), the capacitance is the electrode's surface area [11]. UC/SC consist of two metal foil electrical conductors, organic or aqueous solution of an electrolyte and a ceramic-plastic-glass made membrane porous separator layer. The electrodes are porous carbon materials with higher surface areas possessing higher energy density than the ordinary (traditional) capacitors [14]. Energy stored in a capacitor, $E_C = 0.5*CV^2$. Since $Q = CV$, $E_C = CV*V*0.5 = 0.5*Q*V$. Also, $E_C = 0.5*C*Q^2/C^2 = (0.5*Q^2)/C$. C = Capacitance of the ultra-capacitor (Farad), V = Voltage between the parallel plates capacitor (Volt) and Q = Charge amount across the plates (Coulomb). $C = (\varepsilon_0 * \varepsilon_r * A)/d$. where A = Total surface area of the plates (mm^2), d = distance between the plates (mm), $\varepsilon_0 = 8.85*10^{-12}$ Fm^{-1} (free space permittivity), ε_r = medium relative permittivity.

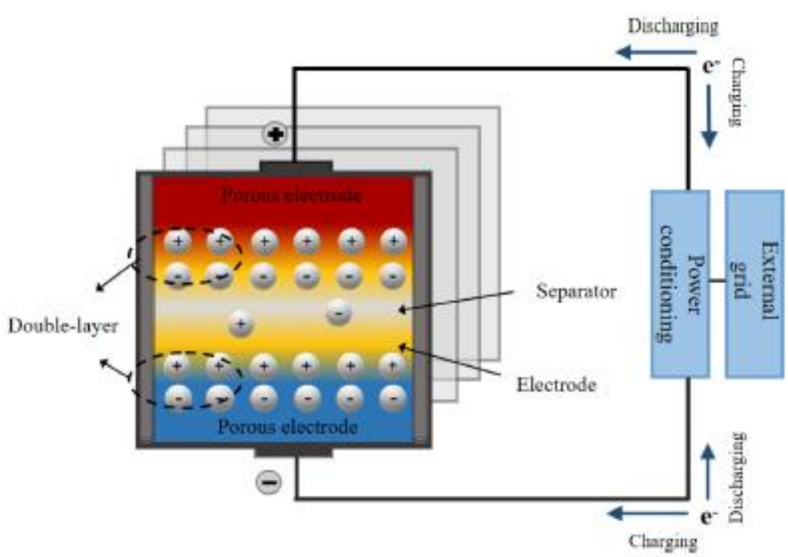


Figure 2: Schematics of Ultra capacitor/Super capacitor [5].

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Table 1: UC/SC Properties

Advantages	Disadvantages
High power densities of 500W/Kg -5000W/Kg Long cycle time greater than 10^5 High efficiency of 85%-97% Fast speed response less than 5 milli-second Long life cycle of 40 years Faster period of charging	High self-discharge rate of 5%-40% per day High capital cost of 6000 dollars per KWh Massive discharge amount of stored energy within a very short time in few minutes

[6-8]

3.0 Non-Series Compensated High Voltage AC System

The real (active) power flow over the transmission lines without capacitor banks (non-compensation) is expressed mathematically below:

$P_{el} = \frac{Ese * Ere}{Xr} \sin \delta^0$ where, E_{se} = sending end internal voltage (volt)

E_{re} = Receiving end terminal voltage (volt), X_r = Reactance transfer of the transmission line (ohm), δ^0 = load angle (degree). Higher power flow limitation production from voltages of higher rating. Reduction of power losses in line current are produced from higher voltage for this same power. The complex design, conductor's size are the factors of constraint on the upper system's boundary transmission voltage level [15].

Fig 3: Waveform of HVAC at Generation with Non-Series/Non-Shunt compensation

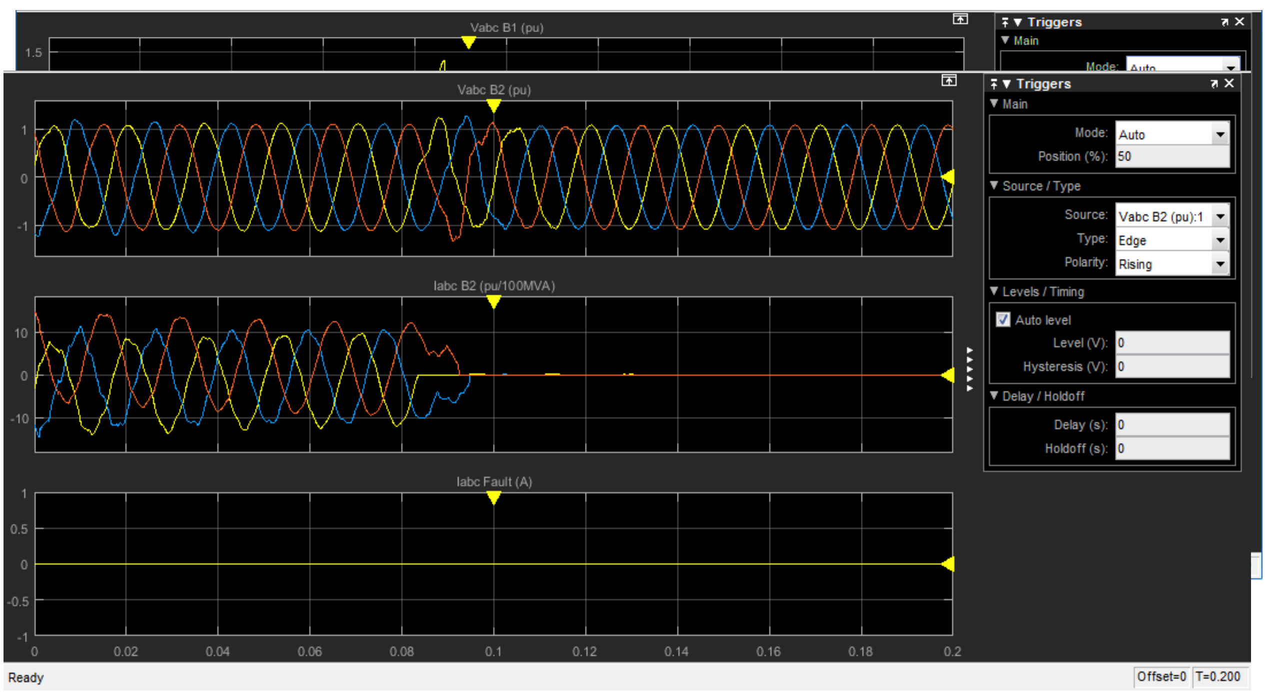


Fig 4: Waveform of HVAC with Non-Series/Non-Shunt Compensation at the load

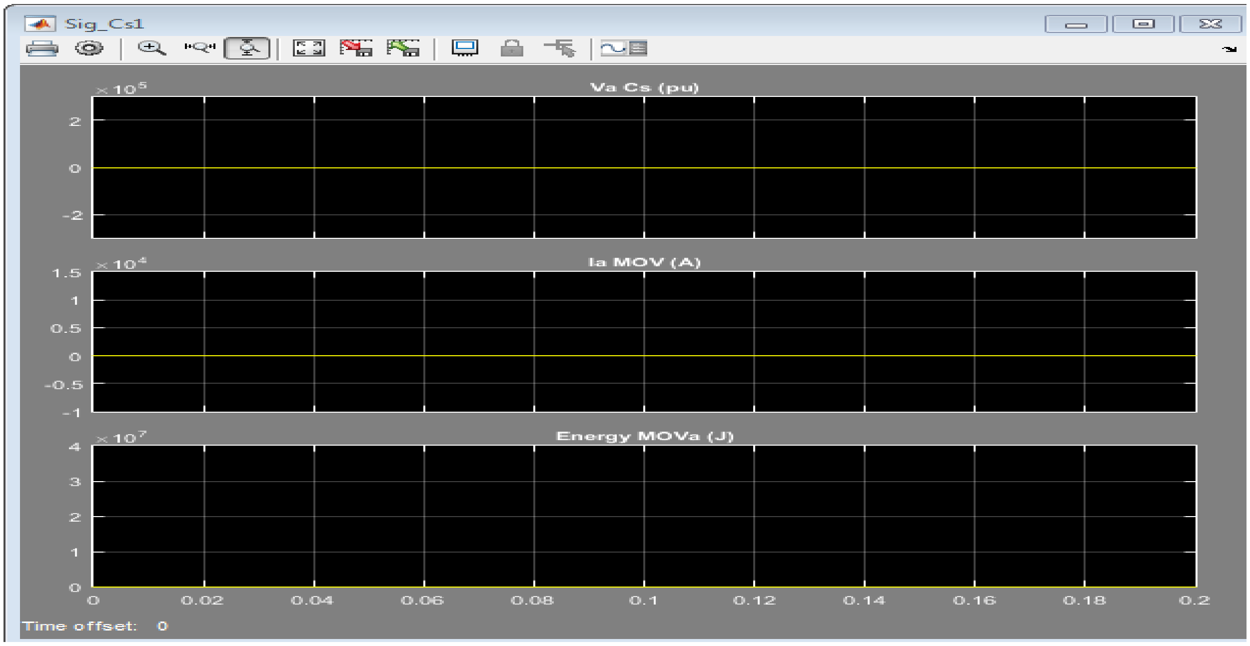


Fig 5: Voltage of Capacitor in Phase A, Current of MOV/ Energy gap without charges

In the line side of the capacitor bank, when fault on the line-ground was introduced in phase A, line1 at first period of cycle, the two circuit breakers (CB1 and CB2) which were initially closed will be opened for a 5-cycle period, simulation of fault detection and the opening period of 4 cycles occur. Fault is being eliminated at 1 cycle period after line opening (6 cycles).

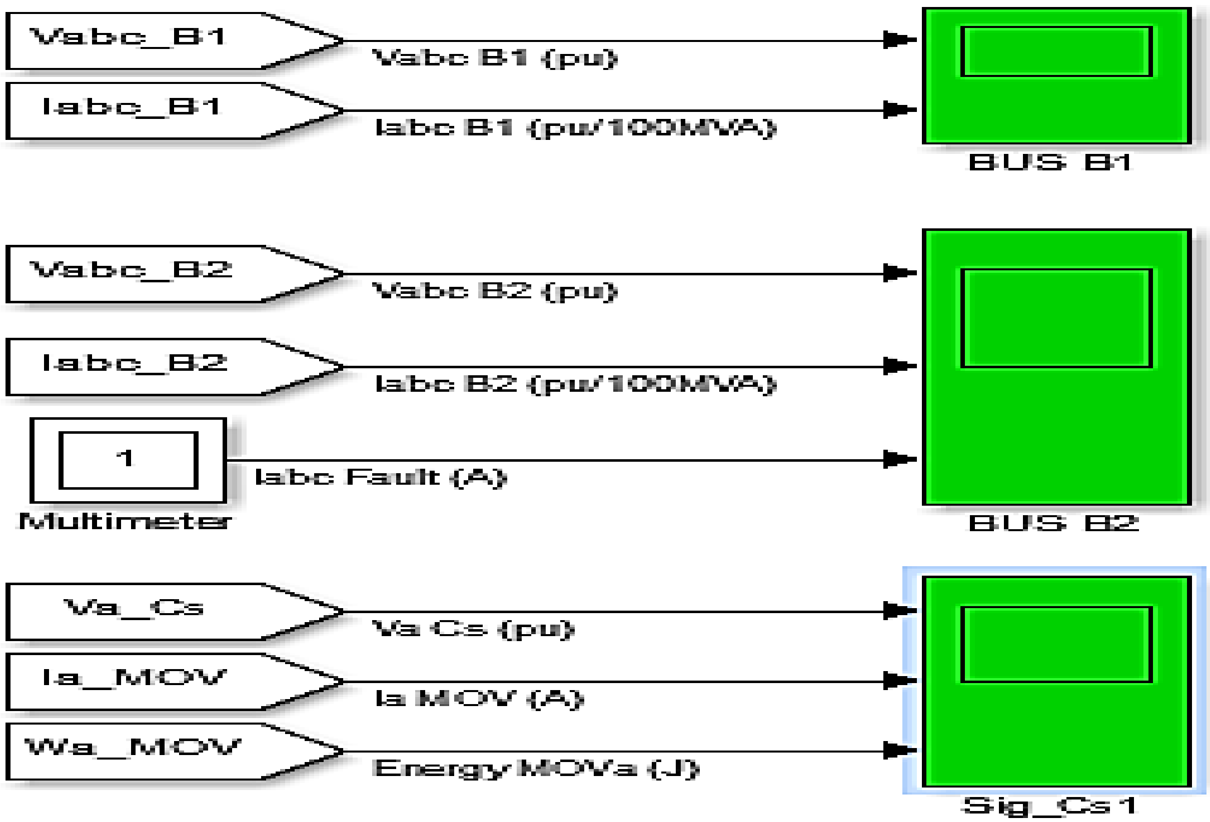
3.1 Power Transfer Potential (Capacity) Enhancement

3.1.1 Series Compensated High Voltage AC System

Before the experience of transient disturbance by high voltage AC power transmission system, there is normal 3-phase power transmission from the power plant to utility load demand with a step-up transformer as the regulator along the line of transmission because of long journey through the first busbar, B_1. The banks of capacitor improve the transmission's potential, production in power qualities, power efficiency and compensation of reactive power provision to reduce harmonics level being developed across the line of transmission being incorporated with metallic oxide varistor (protective device) to control limitation of energy level that the capacitor can accommodate to avoid truncation (burning off) before conveyance through the next busbar (second busbar, B_2) being proceeded by a stepdown regulator known as transformer for reduction in voltage level suitable for the requirement of industrial and consumption unit being the occurrence of distribution[19]. The three-phase voltage and current waveform transmission with no condition of fault on first and second busbars, B_1 and B_2 with the voltage of the capacitor, metallic oxide varistor's (MOV) current and energy gap between the capacitor bank and the MOV was displayed by a data acquisition (signal generator: Sig_Cs 1) below.

Fig 6: Acquired Data from the Sub-System Depicting the measurement of Bus bars (B1 and B2) and Energy gap

The opening of the above subsystem of the unit 1 series compensation of 3-phase series HVAC system model depicts the module of the 3-phase comprises of 3 subsystems that are identical, each subsystem



representing each phase beside the subsystem of the series compensation unit 1. The value of capacitance and protection level of the MOV are determined. Detailed series capacitors in connection and surge arrestor block of the MOV's present in it are further expressed. The connected series capacitor and the metallic oxide varistor block on opening the series compensated, unit 1 of phase A subsystem are illustrated in the detailed diagram depicted below.

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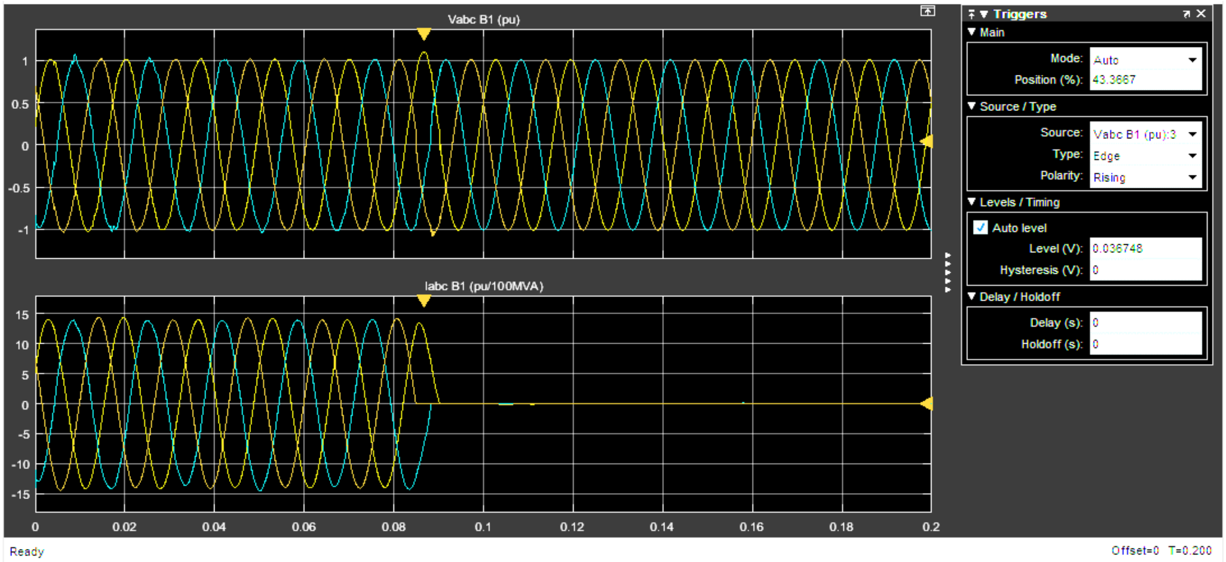


Fig 7: Waveform of Series Compensated HVAC at Generation Source

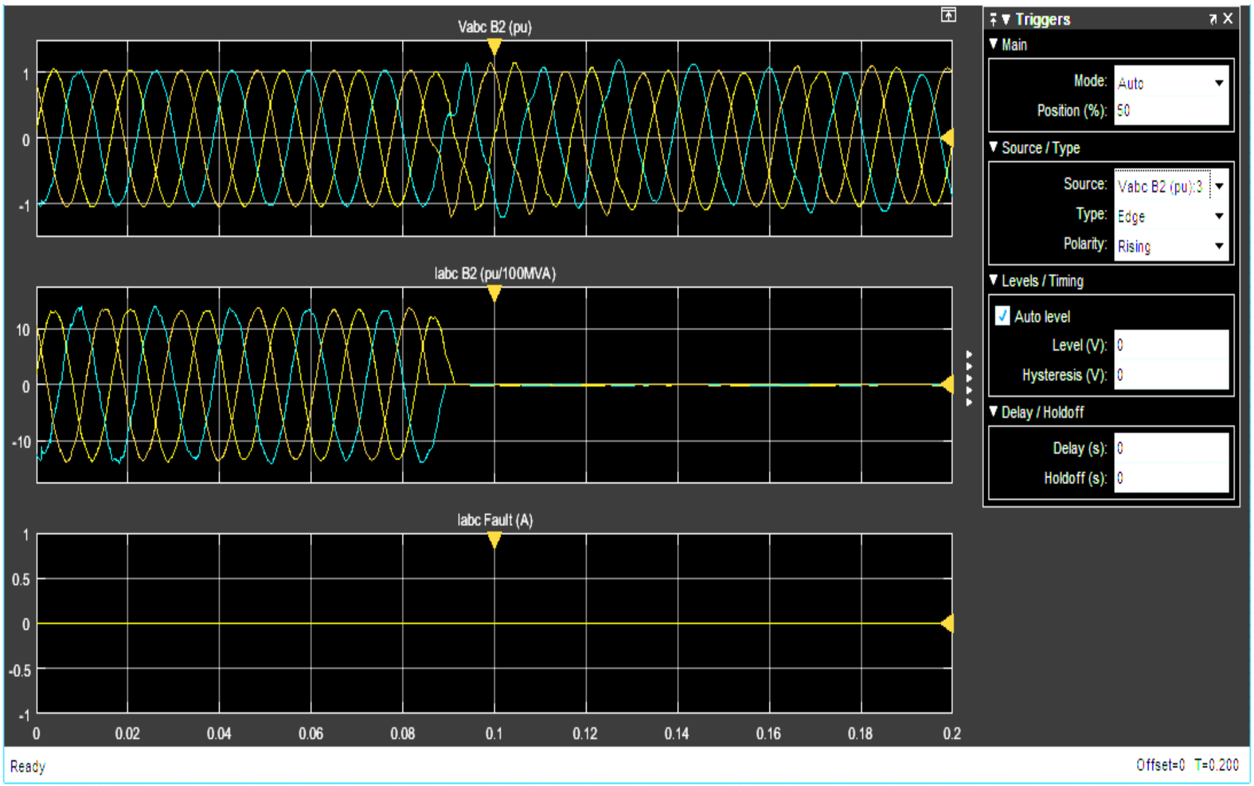


Fig 8: waveform of Series Compensated HVAC at the Load

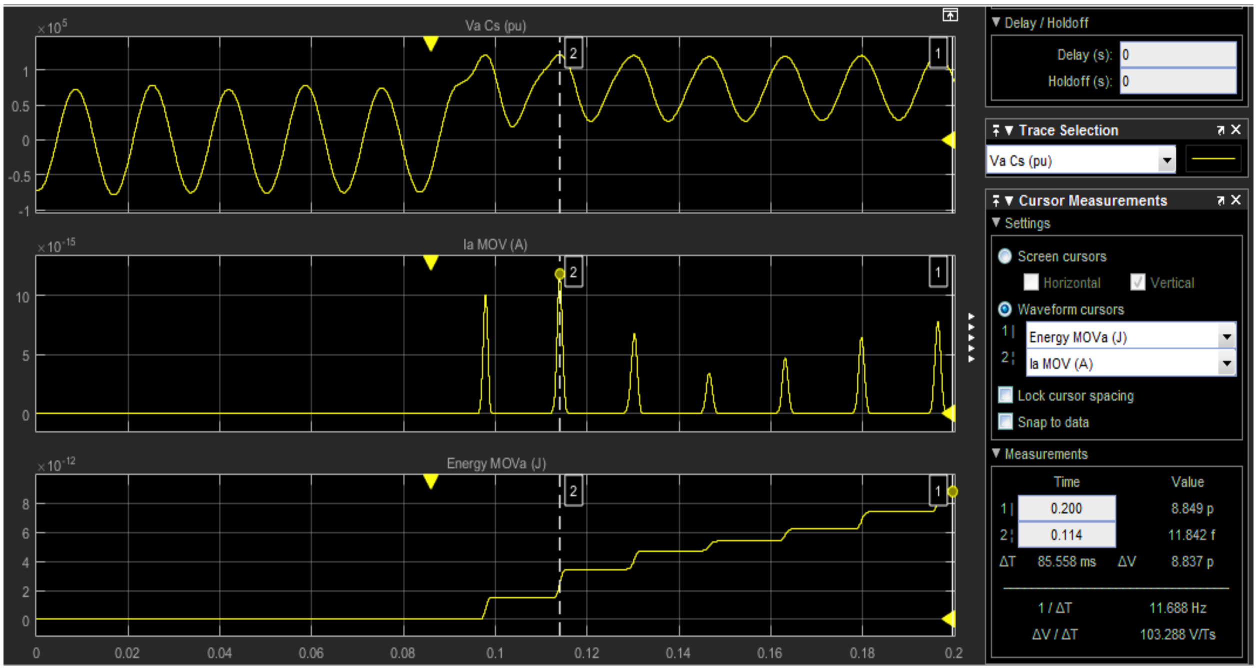
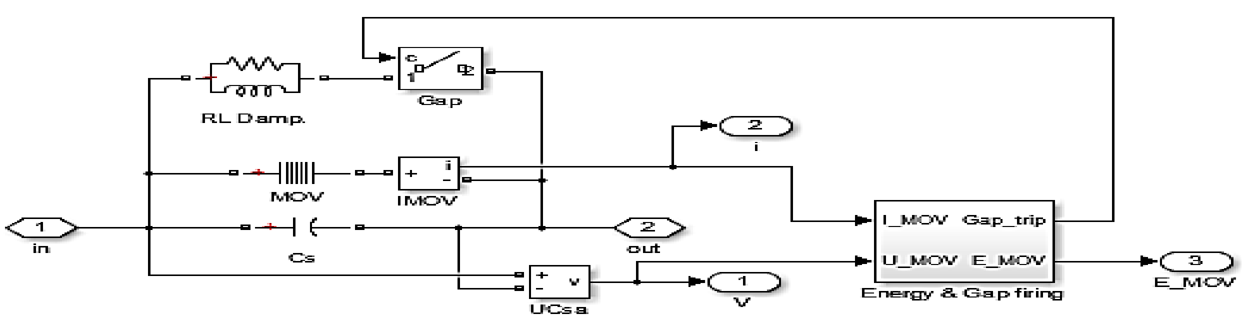


Fig 9: Voltage of Phase-A Capacitor, Current of MOV and Faulty Energy gap

When the sub system unit 1of the series compensated 3-phase HVAC model system is opened, 3 identical sub systems in the 3-phase module (each sub system represent a phase) beside the compensated unit 1 sub system. The value of capacitance in the capacitor with the protection level of metallic oxide varistor was determined. In addition, the detailed series connected capacitor and surge arrestor's block (MOV block) is found in it.

The detailed connection of the capacitors in series and the surge arrestor (MOV) block after opening the sub system unit 1 of the series compensated phase A sub system is depicted below in figure 10.

Fig 10: The Series Compensated HVAC Unit 1- phase A Subsystem



3.1.2 Metallic Oxide Varistor and Airgap/R-L Damper

The type of primary protection system with non-linear characteristic is the varistor, during fault because of larger defective current, there is an increase through the voltage of the capacitor bank, the metallic oxide varistor conducts before the voltage of the capacitor bank approaches its withstanding maximum voltage level. The MOV with its higher non-linearity has the higher potential to limit the voltage of the capacitor bank. Ordering the leakage current through the MOV in milliampere under normal conditions, the MOV provides lower levels of capacitor protection, instant reinsertion, and high reliability. The required conduction level for the protection of capacitor bank by the MOV is 2.50 times nominal voltage of the capacitor bank. The second capacitor bypass bank systems of category are the airgap.

When the maximum energy capacity dissipation across the MOV is being exceeded by high fault level, capacitor bank protection is required with the MOV (zinc oxide varistor). Flashes from the air gap beyond a particular stage of a voltage in few seconds (microsecond) following a fault through fully capacitor bank bypass, the conduction voltage of the air gap ranges from 2.50-3.50 in multiples of nominal voltage of the capacitor. Due to line breakers transmission in operation to internal fault isolation, there is interruption in the conducting air gap. Possession of triggered air gaps by fast protective devices with new arc plasma injection technology connected in parallel with fast contact for difficult avoidance in maintaining air gap electrodes and distance correction. The ever-open position bypass circuit breaker in usage switches the series capacitor in and out during planning operation and bypasses the MOV in service, capacitors in series and the fast protective device if non clearance of fault occurs within a pre-determined time. The bypass breaker must carry the maximum discharge current of the capacitor and rated voltage of the MOV. The purpose of designing rated bypass breakers is to overcome current interruption and high frequency transient as an order when bypassing through capacitors in series. The air core reactor (damping circuit) is connected in series with the bypass circuit breaker and fast protective device (for damping) and limiting the discharge current of capacitor when there is closure in the bypass circuit breaker or triggering of the fast protective device (FPD) [16].

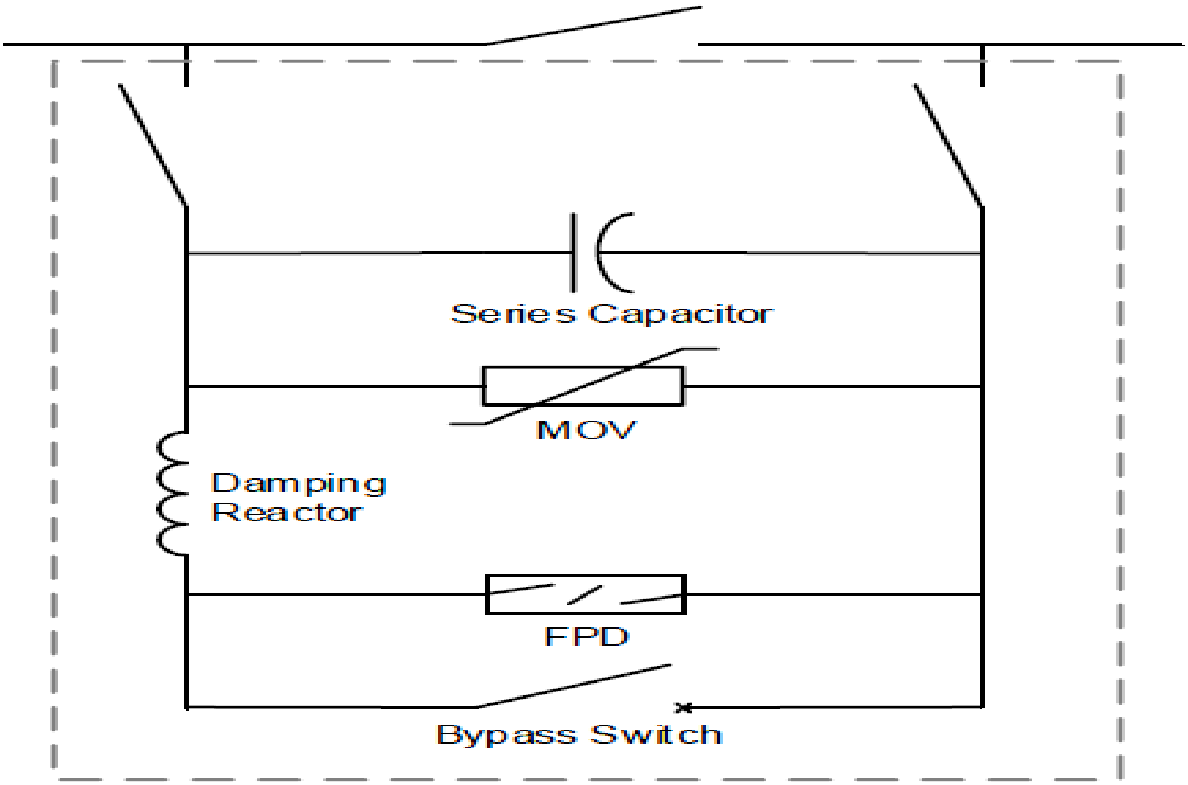


Fig 11: Components of Fixed Series Compensation [16]

3.1.3 Thyristor Controlled Series Compensation System (TCSCS)

The compensation's degree over broad range of various network conditions can undergo optimization by the application of TCSCS for damping of oscillations in active power system's disturbance in connected weak links network. TCSCS provide effective mitigation means when sub synchronous resonance (SSR) arise. When there is blockage in the thyristor gate and full compensation on the line occurs, the capacitor experiences full flow of current across it. When the thyristor gate is at full conduction mode, the capacitor is being bypassed successfully [18]. Across the metallic oxide varistor (MOV) connection with assurance on the capacitor over protection of voltage, for better voltage protection and maintenance, the connection must include a bypass breaker. Most of the TCSCS have fixed level of compensation in combination with variable level of compensation as depicted below.

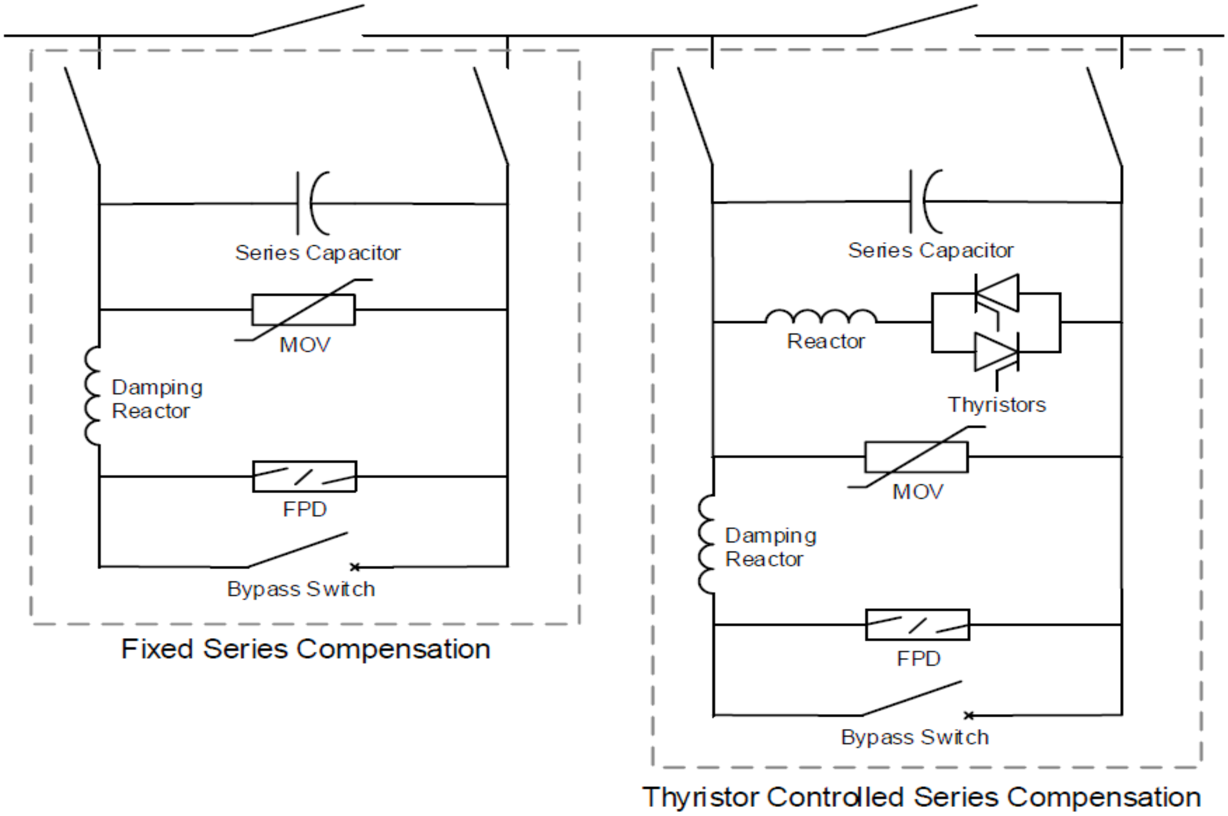


Fig 12: The Components of TCSCS [18]

The TCSCS system have two modules in series connection known as fixed series compensation system (FSCS) and series capacitor in parallel connection with the thyristor-controlled air core reactor (TCACRS) system. The FSCS has a parallel combination of MOV (metallic oxide varistor) over voltage protection, airgap with R-L damper known as bypass circuit breaker and installation of capacitors on a platform being insulated which is elevated to the line voltage for the capacitor bank protection against abnormal or over voltage during faults condition [18].

4.0 Effect of Transient in a Faulty Line

when a transmission line is faulty, faulty current occurs due to massive flow of current through electric network which can result in heavy damages to equipment system being insulated. Thereby causing surge in power that can charge devices for electrocution or possibly truncate/damage powered equipment through current flow. High level of fault in high voltage AC system can affect the generating source unit to the receiving end (entire system) thereby subjecting the generator unit beyond its design limitation, increasing temperature, system distortion, and amplifying the torque in airgap with imbalance flux density. There are 3 types of asymmetric faults which are line-ground fault (line and ground short circuiting together), line-

line fault (two lines contacting each other) and two lines-ground fault (two lines with ground in contact) [17]. The application design of circuit breakers is to clear fault in power system.

From the above model, the high voltage AC power system was approximated for the purpose of simulation speed up, the guide on power block sample time is specified as $T_{sample} = 5.50 * 10^{-5}$sec as applied in the integrated block surge arrestor as calculated for monitoring the energy gap. Expression of simulated parameter is depicted in table 2.

Table 1: Simulated Parameters

Period of sampling (fixed step size)	T_{sample}
Stopping Period	0.300s
Alternative to type of solution	Fixedstep; non-continuous state (discrete)

4.1 Fault in Line-Ground of a High Voltage AC System

On phase A, fault breaker is being programmed for fault online-ground. The simulation has undergone a test and its waveform observed as demonstrated on the three types of scope indicated in the figures below.

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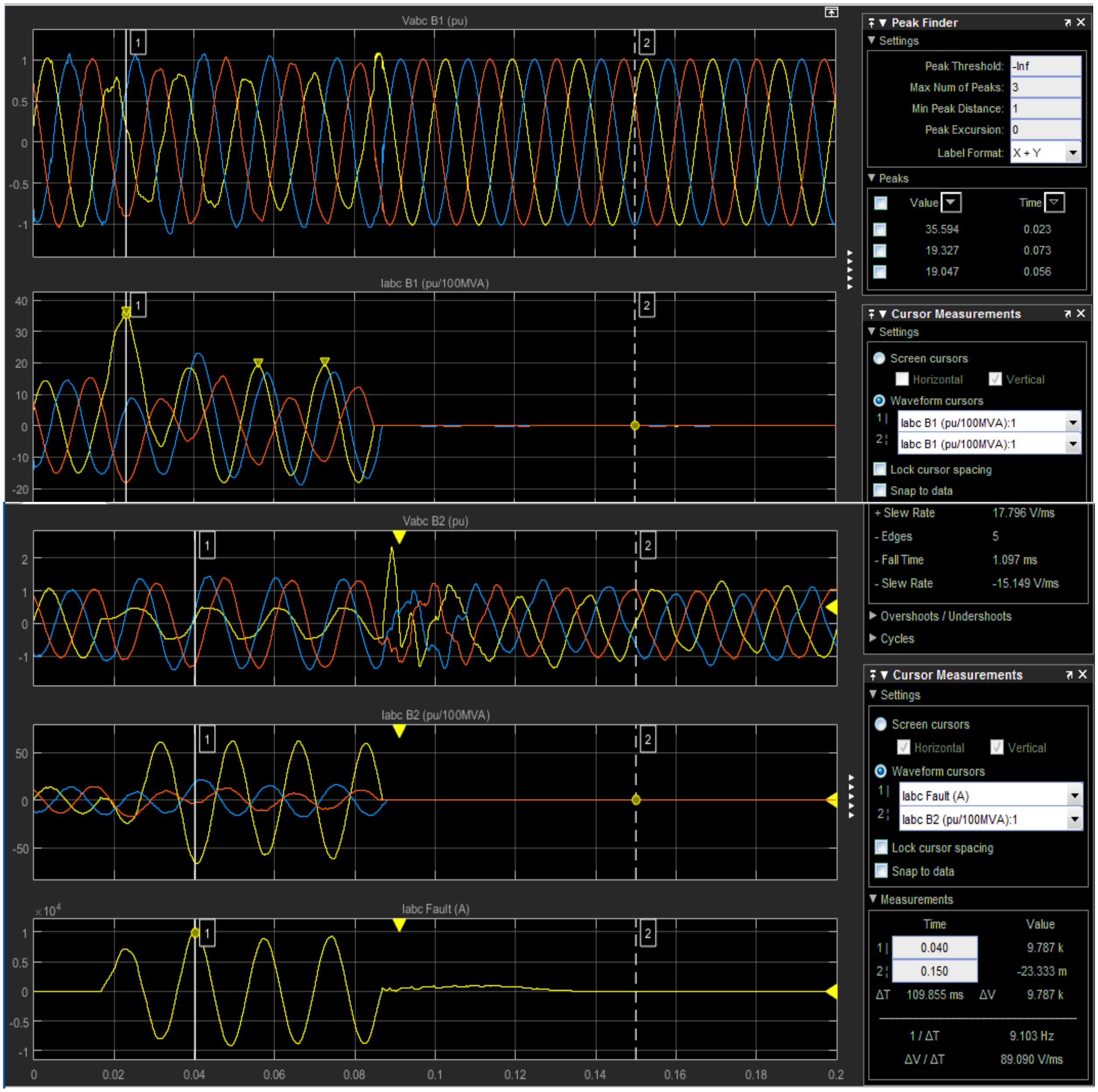

Fig 13: Waveform of Faulty Line-Ground Current on HVAC Series Compensation at Generation

Fig 14: Waveform of Faulty Line-Ground Current on HVAC Series Compensation at the Load

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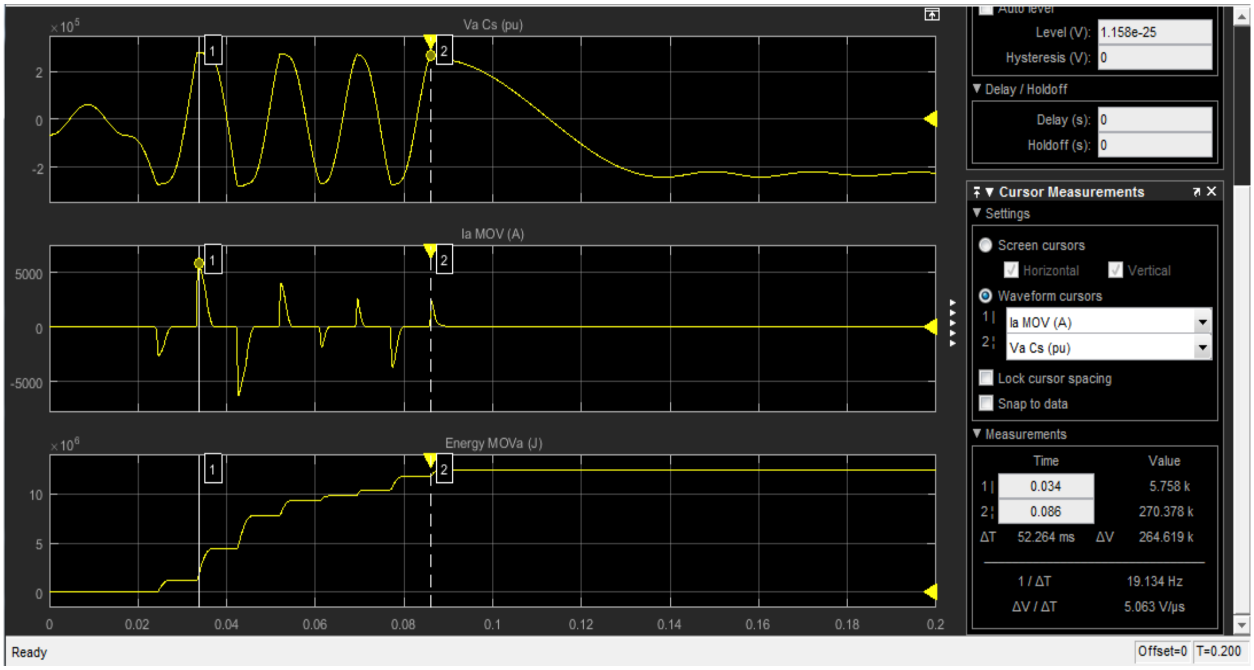

Fig 15: Integrated HVAC Faulty Line-Ground Capacitor/MOV/Energy Gap System

The normal power system operation in a steady state is being simulated. At 1 period cycle, the line to ground fault was applied causing 9.787kilo Amperes faulty value of current (trace 3 of figure 14). The MOV conducts at every half cycle (second trace in figure 15) during faulty period, 15 mega joules of built-up energy are being dissipated in the arrestor (third trace in figure 15). The circuit breakers (CB_1 and CB_2) opening are being triggered by the line protection relay at 5 cycles period (trace 2 in figure 15) and constant energy flow at 15 mega joules since the threshold's level (40 mega joules) is not superseded by the maximum energy, hence gap fire occurs. There is a one-minute drop in the faulty current and discharge commencement of the series line capacitors from fault and shunt reactance when the circuit breaker opens. After a 6-cycle period opening order of the circuit breaker as assigned, the clearance of faulty current at no crossing (first zero crossing) occurs. The series capacitor stops discharging and its potential oscillation is 220 kilo volts (trace 1 in figure 14).

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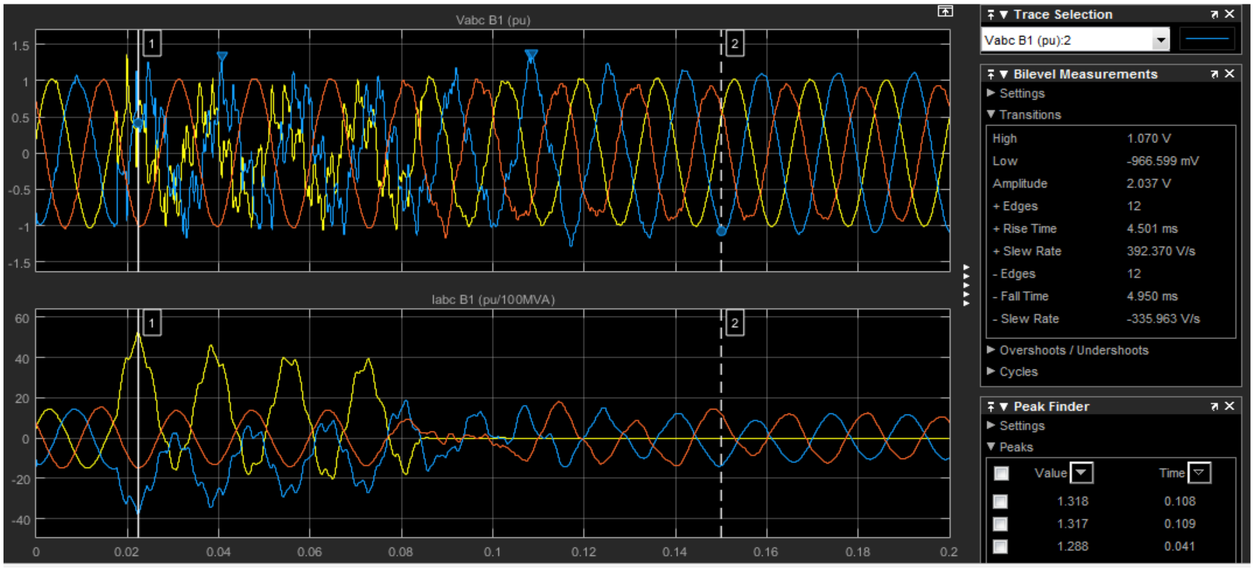
4.2 Line to line fault in High Voltage AC System

There is a short circuit (contact between two lines) with non-involvement of the ground from the waveform below. flow of current occurs between the sending end lines causing more distortion of much higher current.

Fig 16: HVAC Line-Line Faulty System at the Generation Source



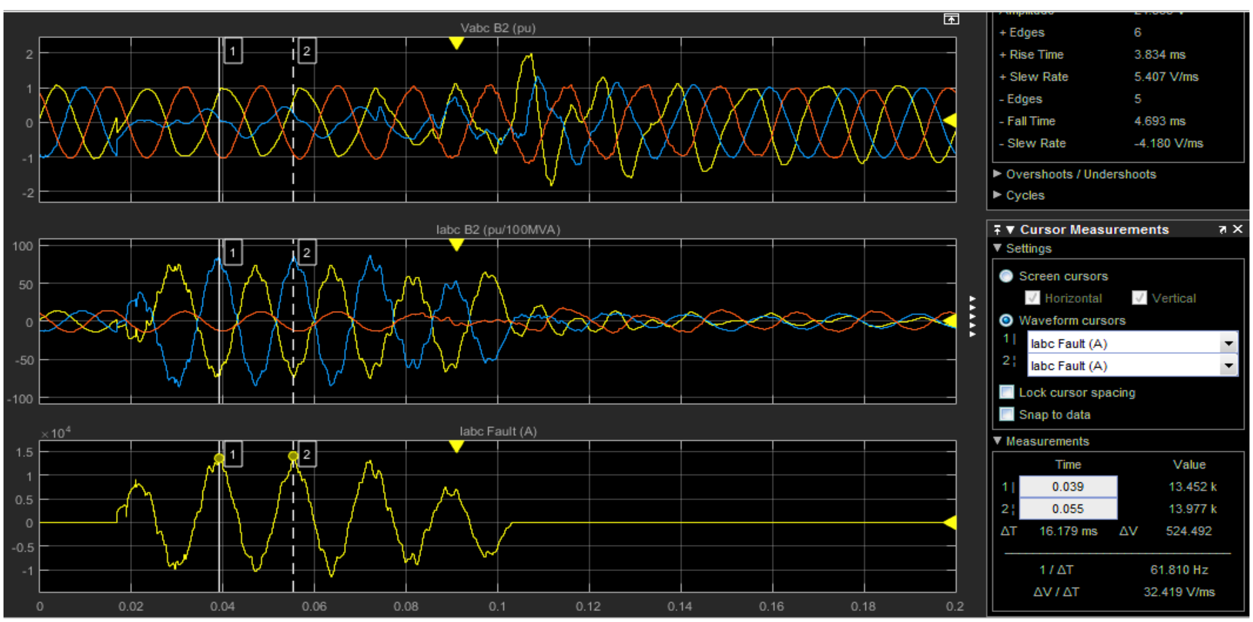


Fig 17: HVAC Line-Line Faulty System at the Consumer Unit

The 13,977A line-line fault current at the second bus bar is another condition for asymmetrical fault in high voltage AC power system causing enormous changes between line currents contacting each other.

4.3 Two Lines-Ground Fault in High Voltage AC System

The faulty circuit breaker was programmed for two lines-ground faults, then observing its behavioural waveform response after running the simulation.

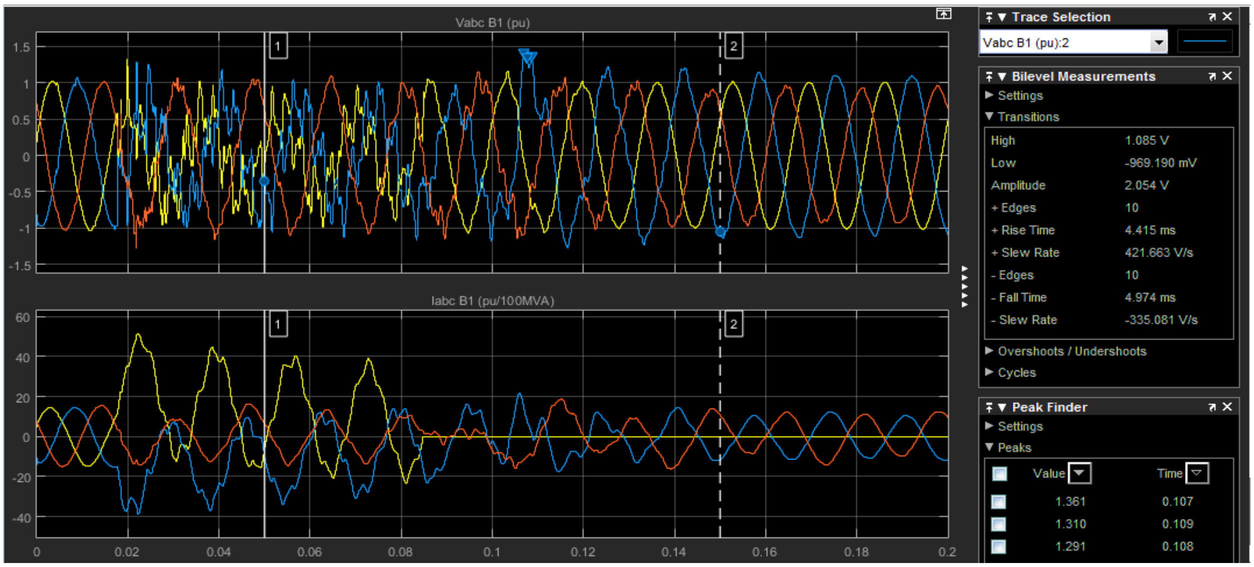


Fig 18: Two Lines-Ground Fault at The Generation Source of High Voltage AC System

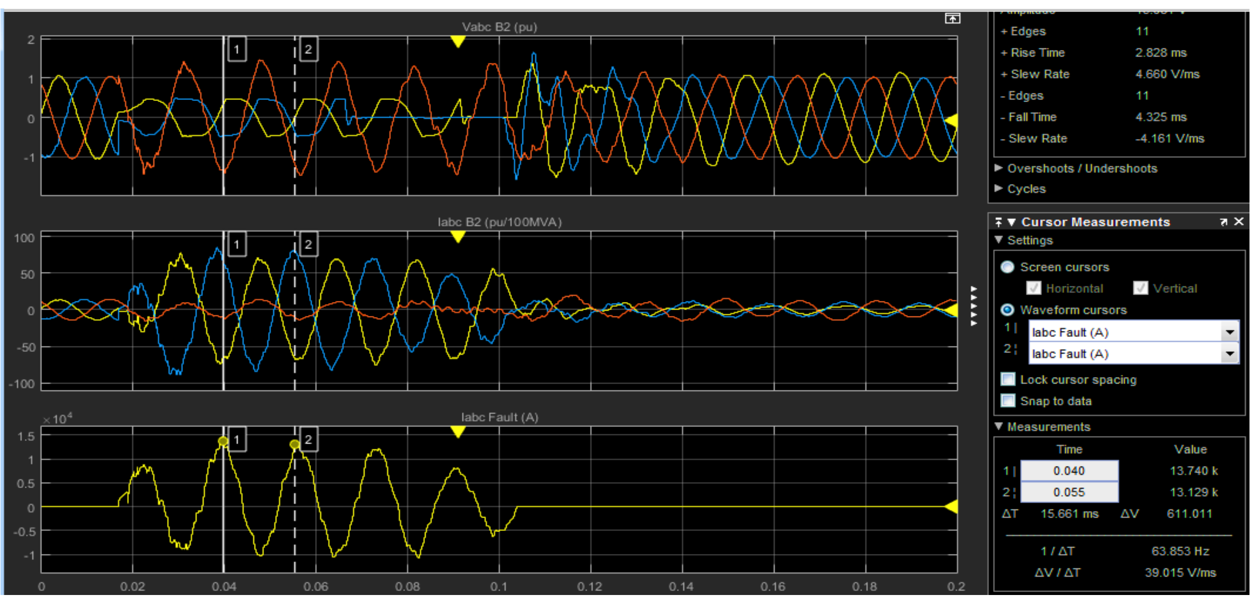


Fig 19: Two Lines-Ground Fault at The Consumer Unit of High Voltage AC System

The double line-ground faulty value of current is 13,740A from the simulation waveform which is greater than line-ground faulty current value of 9787A obviously because of the rated current value for each line.

When each line is in contact with each other and the ground, they produce a massive current flow of the short circuit in the two lines and ground contacting one another.

5.0 Effects of Series Compensation on HVAC Power System

The effects that are mainly behind the series compensation of HVAC power system transmission lines are detailed below:

Provision of control in the load division among several lines when series capacitance is in addition thereby controlling the degree of compensation in the installed bank of capacitors on the several systems of buses. The shared load quantity among the lines can be controlled, providing a better control of load along several transmitted lines. There is improvement in voltage regulation by lower impedance lines through bank of capacitors incorporation into the system of transmission line reduces the net line impedance leading to lesser dropping of voltage across the line with improved regulation of voltage.

Line of lower impedance improves stability when capacitor banks are inserted to the transmission line, rotor angle, δ^0 reduces for the same transfer amount in power because of the effect of compensation. Operation of the rotor at lower angle with increment in limitation of stability at the reduction of load angle (δ^0). The power transfer capacity in transmission lines increases by series compensation. The improvement in transmission system is being utilized by line’s load capacity increment. The power transmission at unchanged voltage level beyond longer transmission lines is permitted by lines in series that are compensated than lines that are non-compensated which is faster rather than additional construction or new parallel lines set [18]. Series compensated lines reduces the net reactance transfer, there is great increment in the power transfer capability of the system as compared to non-compensated line. The power transfer capacity increment procedure in the system of transmission line may serve as replacement over the connection of parallel lines’ need for increase in load demand.

6.0 Conclusion

The HVAC power transmission system was modified by carrying out the integration of its components from Simscape-Simulink power tool application on MATLAB. The power transmission system (HVAC) circuit design was modelled, and its point of power flow was analysed. The step up and stepdown transformers (regulators) with series compensation has influence on the voltage and current of the HVAC power system lines through production of significant output power from measured waveform result. The use of metallic oxide varistor (electronic power device protection) in the high voltage AC power system design improved the quality of power transmission and safety of the capacitor banks (series compensation on the designed HVAC system) justifying the asserted theories. The waveform of power flow is being affected by disturbance effected on the simulation design causing waveform distortion of the 3-phase voltage/current as observed which is a reality in relation to power system operation experience. The alternator's swinging effect when subjected to severe disturbance from the HVAC simulation design was demonstrated with results. The input mechanical power (prime mover) varies through imbalance flow of energy from power generation source to the consumer unit of the power transmission system as evidence that is happening in the real-world power system scenario. The implementation/simulation of the high voltage AC system from modelled experience aims mainly to improve the quality of power transmission, maintain stable operation between the generation source and load demand, increase the transmission potential, improvement in the efficiency of technologies and principle of operation was successfully achieved.

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