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The Simulation Analysis of Shunt Reactor Controlled Switching at 500 kV Network

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***Abstract* — Switching transients are one of the major causes of excessive stresses on the power system equipment, switching apparatus and also create power quality issues along with mal-operation of protective relays. Shunt reactor switching (SRS) is performed to mitigate the Ferranti Effect at off peak hours & if done in an uncontrolled way may have severe consequences. SRS at peak of the source voltage waveform eliminated the inrush current and de-energization at zero crossing decreases the re-ignition or restriking overvoltage surges. This paper analyses the actual science behind point on wave controller (POWC) and its positive effect on power system equipment. A case study of 135 MVAR SRS, installed at 500 kV transmission substation Rahim Yar Khan, is carried out by using PSCAD/EMTDC®.**

***Index Terms*— Controlled switching, shunt reactor, point on wave/cycle relay, re-ignitions, inrush & chopping current.**

I. INTRODUCTION

Generation of electrical energy relies on different factors such as availability of fossil fuel, bulk water supply with head, wind corridor, public safety, load centers and right-of-way. Transmission of electrical energy from generating station to load centers is carried out at MV to EHV levels depending upon the distance between the two and capacity of plant. Every area has its own peak and off-peak hours of energy utilization depending upon the consumer type, time of day and weather conditions. Loading conditions affect the receiving end voltage long lines. Ferranti effect is observed on transmission network when loaded below their surge impedance(s) & the enhanced voltage may damage the substation equipment. Utilities around the world have shunt reactors to cope with this voltage issue. Every shunt reactor is usually switched ON when voltage is above 105% and OFF when below 98% value and is usually done twice or more times a day depending upon peak and off-peak hours [1]. Its energization and de-energization have inrush current & transient recovery (TRV) or re-ignition voltage issues respectively. Previously different methods have been utilized for smoothing switching action and dampen out the TRV on HVCBs. Employment of suppressing resistors; damping reactors and protective surge arrestors have shown acceptable level of disturbances on system parameters during switching actions but quest for best has advances the science of switching to the advent of POWC. This new technique is not only avoiding the production of abnormal operating conditions but also has reduced and maintenance cost & frequency of shunt reactor circuit breakers. In Pakistan, European & USA based POWC are employed for catering the SRS issues, capacitor banks and to some extent unloaded lines. This paper discusses various methods, including POWC used for the energization and de-energization of shunt reactors.

II. ENERGIZATION OPERATION

Shunt reactor energization (SRE) is carried out when lines are loaded below their surge impedance given by (1). Surge impedance of OHTLs is normally in the range of 400-450Ω, power cables 40-45Ω and transformers in the range of thousands of Ohms.

$$Z_o = \sqrt{\frac{L}{C}} \quad (1)$$

In an ideal shunt reactor, the relationship between voltage and current shows that current is always lagging behind the voltage by quarter of a cycle. When voltage is at its peak then current will be touching the zero line and vice versa as shown in Figure-1. This lag-lead feature can be utilized to minimize the inrush current during SRE operation.

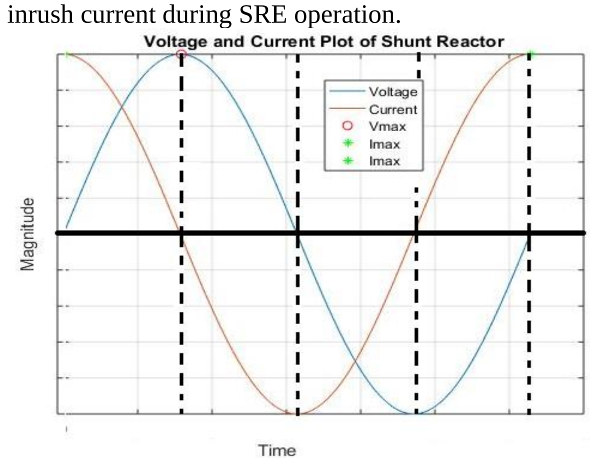


Figure 1: voltage and current waveform in reactor

Transmission lines loaded below their natural impedance will behave like capacitors providing MVARs to the system and causing Ferranti Effect whereas heavily loaded lines will be acting like reactor absorbing MVARs [2]. Additional MVARs of lines, during low loading times, are absorbed by switching ON the shunt reactors usually connected at both ends of EHV transmission lines and are kept OFF during peak loading hours [3]. Particularly in Pakistan, peak hours are considered twice a day and are also depend upon other factors. Energization of shunt reactors at random instants has many disadvantages and therefore this approach is replaced by switching at strategically selected points of source voltage. This controlled switching minimizes the abnormal operating conditions (inrush current, harmonics and excessive stresses) to the power system at large and circuit breaker at the first. In three phase system peaks of voltages and currents signals are always in reverse order in which it is connected i.e for a system connected in 0-4-8 (RYB) manner, the peaks will come in 0-8-4 (RBY) way and vice versa as shown in Figure-2. Naturally the phase peaks are T/3 time away from each other so the closing operation does follow the same sequence of peaks. **[4].**

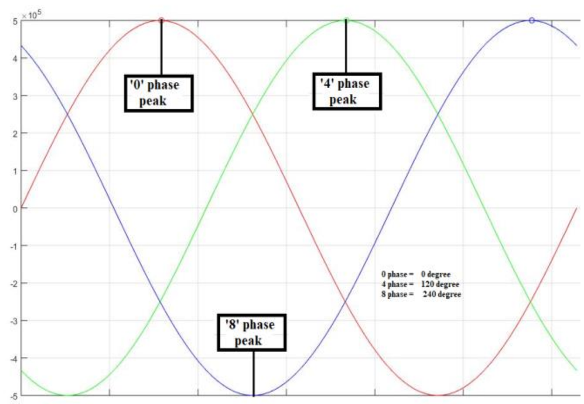


Figure 2: Three phase voltages and peaks

A. *CONVENTIONAL CLOSING OPERATION*

Magnitude of inrush current, transients, waveform distortion and system surges depend upon the instant of source voltage at which pulse is generated for closing operation and inherent time of operation of circuit breaker to make the contact. If by chance circuit breaker contacts are made at the peak of source voltage the no abnormal operating conditions are faced by system equipment(s) and, on the other hand, if not then all the effects discussed above will be on circuit breaker and other allied system and load apparatus. These severe consequences of switching transients on the equipment are minimized by pre-insertion resistors or reactors or installation of surge arrestors of suitable limits.

B. *USEFUL TERMS IN POWC SWITCHING*

Some useful terms in the controlled switching operation of CBs are given below and shown in Figure-3:

i. CLOSING TIME ($t_{closing}$)

Time between energization of closing coil and CBs contact touching moment.

ii. MAKE TIME (t_{make})

Time between energization of closing coil energization and instant of current flow through CB. Adaption control of POWC IEDs (Intelligent Electronic Devices) adjusts the making time. It is mainly linked with pre-arcing time changes.

iii. PRE-ARCING TIME($t_{pre\text{-}arc}$)

Time between flow of current through CBs and physical touch of CBs moving and fixed contacts.

$$t_{pre\text{-}arc} = t_{closing} - t_{make}$$

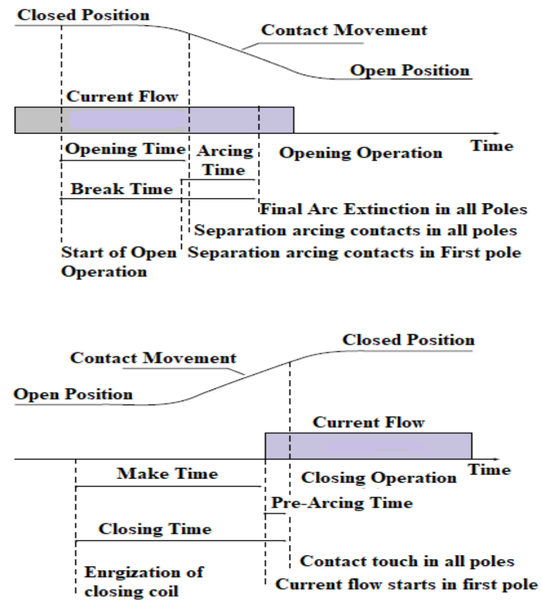


Figure 1: Time definitions according to IEC61271-100

iv. ARCING TIME(t_{arc})

Time between current separation and current interruption in CBs.

v. WAITING TIME(t_{wait})

Time between refrence point and initiation of switching command.

vi. OPENING TIME(t_{open})

Time between energization of opening coil and CB contact separation moment. This time also includes the time required for essential auxiliary equipment operation of CBs.

vii. IDLE TIME(t_{idle})

Time between switching operation of CBs i.e closing operation to opening operation time and vice versa. This time also effects the operating time of CBs mainly with hydraulic mechanism of operation and maximum of 1.3 ms delay is seen after 1000 hours of idle time This effect is rarely seen in frequently & spring operated SF_6 based CBs **[5].**

i. CONTROLLER TIME(t_{contr})

Intentional synchronizing delay introduced with respect to reference point.

ii. RRDS

Rate of recovery/rise of dielectric strength (RRDS) of CB. It depends upon the time of opening operation, contact separation and surface conditions.

iii. RDDS

Ratio of pre-strike voltage to pre-arcing time of CBs is termed as rate of decrease of dielectric strength. RDDS mainly depends upon the contact gap and nearly a direct relation is observed with it. For an ideal CB it will be considered infinity however if it is less than system voltage then pre-arcing will happen during closing operation. Optimum closing target can be calculated by using this parameter. CIGRE WG 13.07 proposed a test sequence after every 15° electrical to find this. Usual pre-arcing time in modern CBs is approx. 6% of total time period of a signal [6]. When the RDDS is 1 p.u then it actually changes in the same line as system voltage at zero crossing and for 100 kV system (RMS) its value is 25.7 kV/ms.

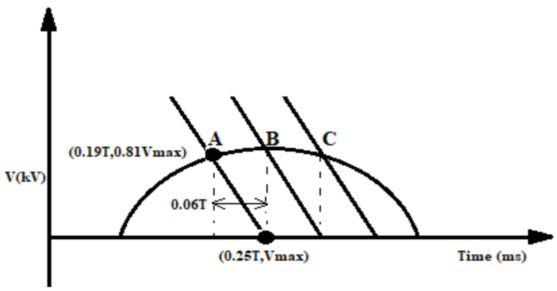


Figure 4: Optimum closing time for shunt reactor

C. POWC BASED CLOSING OPERATION

Shunt reactors are either solidly grounded or through some resistor or neutral reactor according to secondary arcing of power network **[3].** Whichever is the method of grounding of reactor, the first pole will be closed at the source voltage peak. Switching controllers are usually operated in two modes i.e. fixed and random. In fixed mode 0/A phase will always be switched first and then others as discussed earlier. POWC IEDs need auxiliary voltage, ambient temperature & idle time sensor's input and frequency measurement mechanism for optimization of next switching operation instant. Decrease in auxiliary voltage, gas pressure and increase in idle time and ambient temperature increases opening time of CBs and vice versa by a factor which may vary with every manufacturer a little bit**.** Adaptive algorithm checks for changes in frequency from reference voltage (bus voltage) too and finally decides the switching instant to minimize the transients. One and half scheme needs more control per CB and modified control mechanism. POWC are smart enough to bypass the controller operation during system contingency for 120 ms in 50 Hz System [6]. Closing of shunt reactor at random times produces asymmetric currents and cause excessive electromagnetic stress on controlling CB, reactor windings and also causes mal-operation of ANSI-50/51 type protective relays installed for zero sequence current path of reactor due to excessive harmonic content.

D. POWC BASED OPENING OPERATION

Shunt Reactors are installed at the two ends of high tension lines for absorption of excessive reactive power generated by line during off peak hours. Usually power systems faces daily two peak hours lasting for 2-4 hours each and are weather and other factor dependent. Shunt reactors are manually de-energized during peak hours and infrequently face tripping on faults.

When reactor is de-energized then magnitude of breaking current is not an issue but (i). Chopping current at pre-mature instants (other than zero crossing) may result chopping over voltage caused with some natural oscillating frequency upto 5 kHz and by the (ii). Re-striking/Re-ignition voltage phenomenon having oscillating frequencies of several hundred kHz have reportedly caused many failures of shunt reactor and allied equipment. Over voltage caused by chopping current (De-energizing reactor when load current is not at zero crossing) phenomenon has less severity as compared to re-striking over voltage (Over voltage caused by de-energizing reactor at reference voltage peak or zero crossing of load current) . Re-ignition occurs when the arcing time is short and severe kind of high voltage and frequency transients are faced by shunt reactor, controlling breaker and allied equipment up to two nearby busses connected.

E. CIRCUIT BREAKER FOR POWC BASED SWITCHING OPERATIONS

Three and single pole breakers are used for controlled switching operation of shunt reactor and capacitor banks for voltage profile/stability improvement of system. Three pole circuit breakers with mechanical staggering can only be used for one POWC operation (closing/opening) accurately. For 50 Hz system of Pakistan, the two poles ($R/L_1/0$ & $Y/L_2/4$) are operated simultaneously whereas third phase ($B/L_3/8$) is delayed for $1/4^{th}$ of cycle time and this kind of mechanically staggered CBs with 1.5 value of first pole to clear factor are used for capacitor bank switching along with POWC controllers. Usually shunt reactors are installed at 220kV & 500kV primary transmission system of NTDCL and with single pole SF^6 based CBs. As per recommendations of IEEE & IEC standards, Puffer type SF_6 CBs uses at least two chambers for 500 kV systems.

III. CASE STUDY

NTDCL has the responsibilities of construction, operation and maintenance of the 220kV, 500 kV AC and 660 kV HVDC transmission system of Pakistan. At the two extreme ends of every long-distance AC line, a bank of single phase (Wye connected) shunt reactors is installed for voltage profile stability. For switching operation of these reactors POWC controllers with single pole (C2 type SF_6 based) CBs are installed. A newly built 500 kV Substation located in Rahim Yar Khan, a last district of Punjab province, has modern POWC based switching system as shown in figure 5.

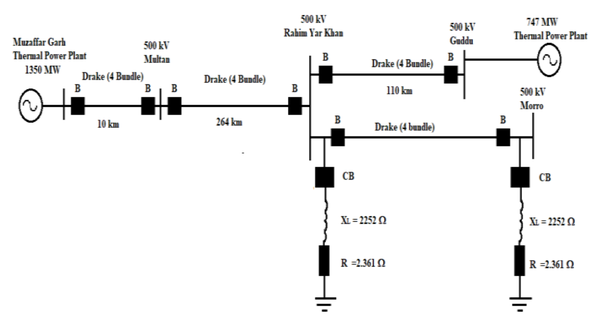


Figure 5: Single line diagram of 500 kV system

Shunt reactor is switched ON if the line voltage is more than 1.05 p.u. and OFF when below 0.98 p.u. Details of shunt reactor are given in table-1.

Table-1

Sr. No	Parameter	Value(s)
1	Rated Voltage	$550/\sqrt{3}$ kV
2	Rated Power	44770 kVAR
3	Rated Current	141 A
4	XL @50Hz	2252 Ω
5	R @ 75°C	2.361 Ω
6	Losses @ 75°C	79.07 kW
7	Connection Type	Single phase, Wye connected solidly earthed (YN)

The optimum and worst closing and opening times for solidly earthed single phase shunt reactor bank is given in table-3 and table-4 respectively. In this paper we will simulate the given system in PSCAD and perform the switching of shunt reactor CBs after every 100 µs and will measure the Inrush current during closing operation and switching over voltage (SOV) across breakers terminals in de-energization process as shown in Figure-6. The stray capacitances, used in PSCAD model are taken from Capacitance & Dissipation (C&DF/Tanδ) test across the equipment and IEEE Std. 37.11, details are given in the table -2.

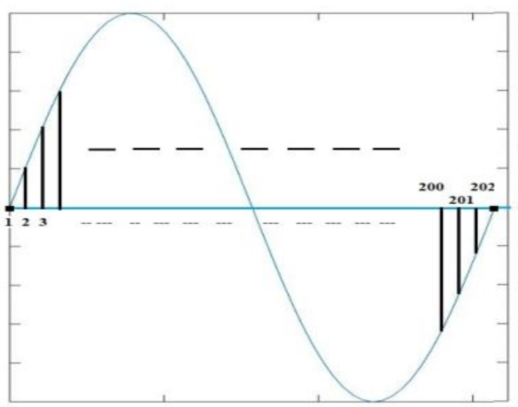


Figure 6: Switching operations after 100 us

Table-2

Sr. No	Equipment	Capacitance (pF)
1	CVT (outdoor)	5500
2	Current transformer	200
3	Voltage transformer	200
4	SF6 to air bushing	100
5	Surge arrestor	80
6	Earthing switch	50

A- Closing Operation & Results

Total 202 closing operations are performed by using PSCAD with CB closing in three pole operation mode without any mechanical staggering between the poles and magnitude of inrush phase currents with closing instants are recorded shown in figure 7. It is evident from this figure that magnitude of the inrush current is minimum at some points whereas at the

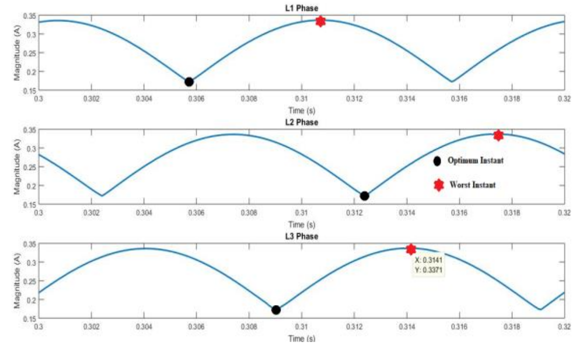


Figure 7: Closing operation on a complete cycle

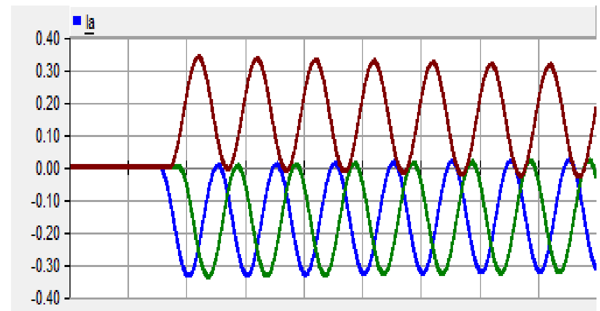


Figure 7-1: Worst case closing current waveform

other extreme on some other specific points. Optimum and worst points for CB closing are noted and are

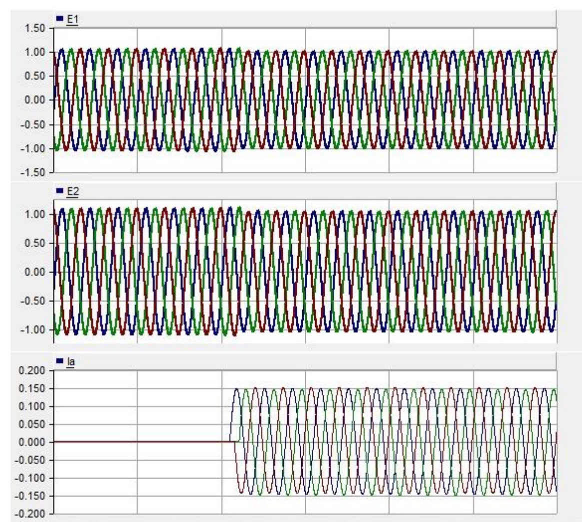


Figure 8: Voltage at RYK end(E1), morro (E2) and reactor current

shown in Table-3. Here the 300 ms is the delay which F236 POWC controller will take before any switching operation (inherent breaker operation time is not considered in simulation) as discussed earlier.

Table- 3

Sr. No	Instant Type (Closing)	L1 (ms)	L2 (ms)	L3 (ms)
1	Optimum	305.7	312.4	309.1
2	Worst	310.7	317.4	314.1

When shunt reactor is switched ON, voltage at RYK end (E1) and Morro end (E2) are decreased about 5% which is also visible from the Figure-8 and the symmetrical shunt reactor current at these instants validate these instants for energization purpose**.** In worst case closing instant, the neutral current as shown in Figure:8-2 may cause erroneous tripping of 50/51 relays.

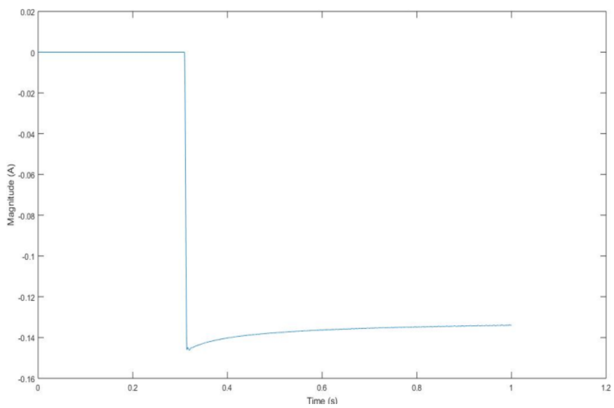


Figure 8-2: Neutral current of shunt reactor at worst closing operation

B- OPENING OPERATION & RESULTS

CB opening operation is needs more care than closing operation when shunt reactor switching is discussed. SOV of as long as **20 p.u** may be observed across the breaker terminals if not opened in controlled mode. Opening operation also involves stray capacitances of all the network equipment across the CB terminals and even the between the shunt reactor windings which

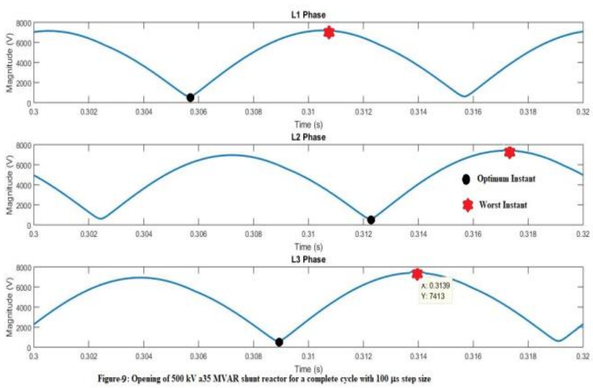


Figure 10: Opening operation at a complete cycle

create high frequency oscillations of SOV phenomenon occurs upon switching (Re-ignition/Re-strike) as discussed earlier. Reference literature of F236 IED of ABB mentions the de-energization strategy as positive

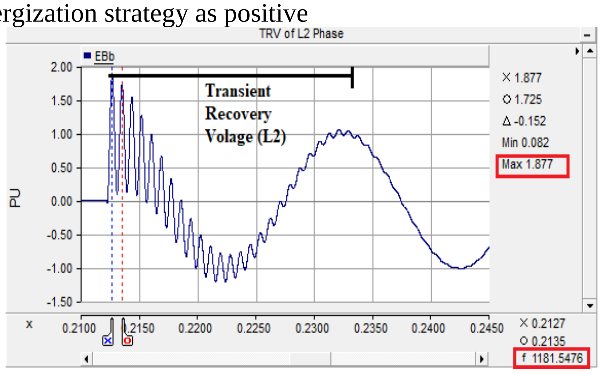


Figure 7-2:TRV across L2 phase on optimum opening

going current zero of lead phase and then next two phases of any phase sequence with a delay of 6.66 ms and 3.33 ms respectively.

De-energization of shunt reactor improves the voltage at the two ends of RYK-Morro line more than 5% which is also visible from the Figure-9.

Table-4

Sr.No	Instant Type (Opening)	L1 (ms)	L2 (ms)	L3 (ms)
1	Optimum	305.7	312.2	308.9
2	Worst	310.5	317.2	313.9

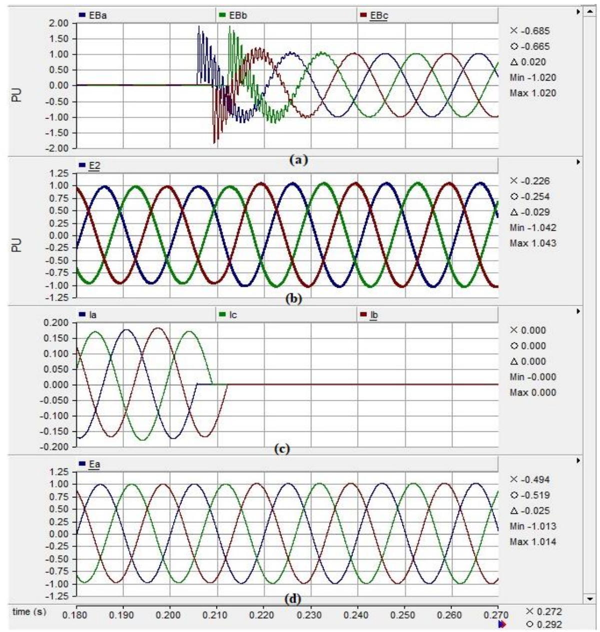
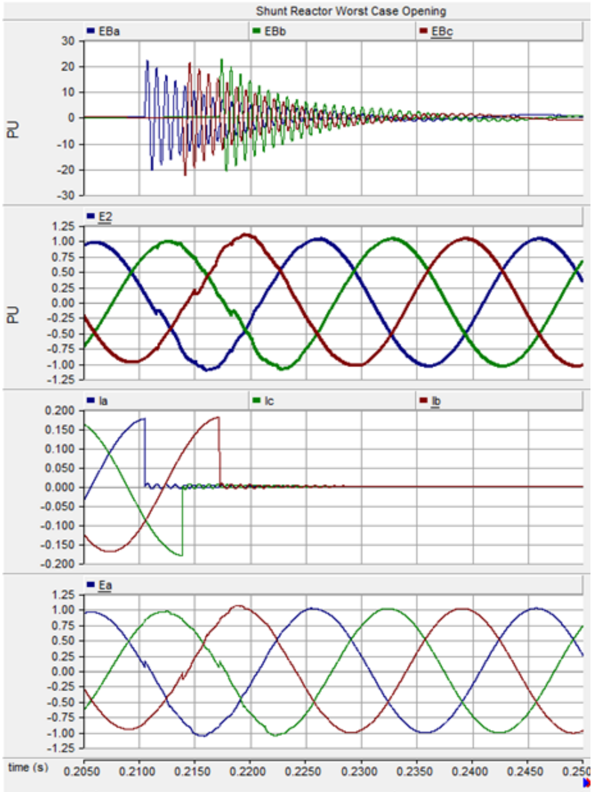


Figure 2: Voltage across CB terminal on optimum opening operation (a)Three phase system voltage at Morro end (b)Three phase current through shunt reactor (c)System voltage at RYK end (d)



From Figure-10 it is also evident that when de-energization is carried out at optimum instant, voltage across CB terminals of shunt reactor is below 2.0 p.u and no effect on system voltage at RYK and Morro terminals is observed. TRV of more than 20 p.u across CB terminals, voltage waveform distortion at RYK and Morro Terminals and shunt reactors current waveform

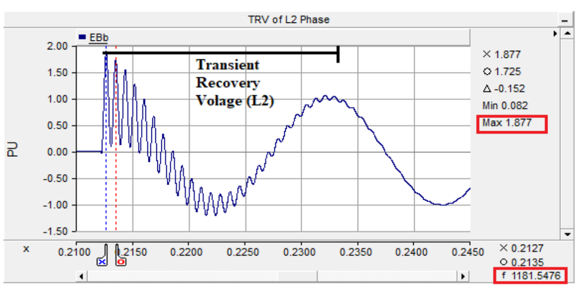


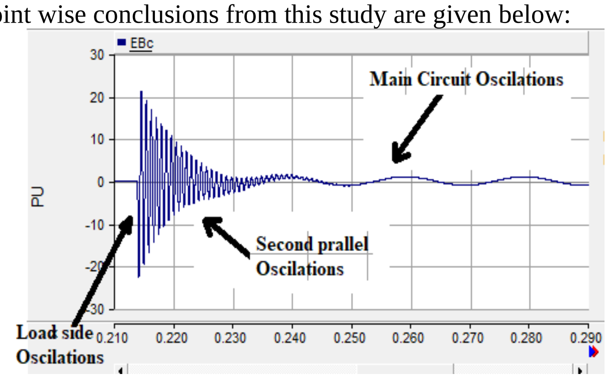
Figure 10-2: TRV across optimum opening operation

distortion is observed across CB terminals on worst case instants as shown in Figure 10-1. TRV across CB terminals in both optimum and worst-case opening lasts for about 40 ms and have frequency of 1.812 kHz as shown in Figure 10-2.

TRV frequency depends upon the L & C values of circuit on both side and characteristics of CB itself. If its magnitude is higher than dielectric strength of the CB then it may cause dangerous re-ignition phenomenon. Re-ignition over voltage are steep natured transients and have rise time in µ-seconds as shown in Figure 11 and can cause non-uniform voltage distribution across shunt reactor windings **[1].** POWC controller ensures that contacts of CB are separated before current interruption to avoid re-ignition. Here the second parallel oscillations have frequency of 1.1812 kHz and main circuit keeps on oscillating with system frequency (50Hz).

IV. CONCULSION

Point wise conclusions from this study are given below:



- Opening of shunt reactor in uncontrolled manner may cause severe SOV across CB terminals and windings which depend upon POWC and CB characteristics.
- In worst case opening operation SOV across CB terminals may increase to dangerous level many folds higher than system voltage.
- Worst case opening may also cause system voltage waveform distortion and harmonics issues for protective/system equipment up to two busses.
- Frequency of TRV/Re-ignition voltage depends upon the system parameters and CB characteristics.
- Duration of TRV/Re-ignition voltage is always less than 3 cycles and for multiple re-ignitions it will be increased accordingly.
- In worst case closing operation, neutral current of shunt reactor may cause erroneous trippings.
- Optimum/worst closing and opening instants for shunt reactor are same.
- The difference between switching instants (recommended & found in this study) is less than 1% which validates them.
- POWC controller can effectively carry out the shunt reactor switching operation and may eliminate the resistor/inductor based switching.

IV. FUTURE WORK

This study will be continued for effects of surge arrestors on switching surges &50/51N
Relay behaviour when closing operation is performed in controlled/un-controlled manner.

V. ACKNOWLEDGEMENTS

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