Effect of shunt reactor rating on the switching transients overvoltage in high voltage system

Mazyed A. Al-Tak[1,2], Mohd Fadzil Ain[1], Omar Sh. Al-Yozbaky[2], Mohamad Kamarol Mohd Jamil[1]
[1]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Penang, Malaysia
[2]Department of Electrical Engineering, College of Engineering, University of Mosul, Mosul, Iraq

Article Info

Article history:

Received Feb 27, 2023
Revised May 3, 2023
Accepted Jun 4, 2023

Keywords:

ATP-draw
Chopping overvoltages
Controlled switching
Current chopping
Shunt reactor
Switching operations

ABSTRACT

This paper includes a computer simulation of switching transient overvoltages during the disconnecting of shunt reactors (SR). Based on the results of the transient simulations, two reactors (150 MVAr and 50 MVAr) were examined. Reactor current interruption causes significant overvoltages, especially across the reactor and the circuit breaker (CB). The severity of these overvoltages may surpass the voltage level, which might endanger the reactor's insulation and accelerate the CBs ageing process. For this reason, a significantly modified circuit model is proposed. The results of the field testing showed that the proposed modified circuit technique was successful. The transient overvoltages were computed using ATP-draw simulations of the equivalent circuit during switching. Successful synchronous switching could decrease the electromagnetic and mechanical stress generated during frequent switching operations. The model was examined the switching transient overvoltage for different values of current chopping (0-20) A. The proposed model proved that the reduction of the overvoltage was 86% in case of (50 MVAr) shunt reactor rating and 87% in case of (150 MVAr) shunt reactor rating.

Corresponding Author:

Mazyed A. Al-Tak
School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Engineering Campus
Nibong Tebal 14300, Penang, Malaysia
Email: mazyed.altak@uomosul.edu.iq

1. INTRODUCTION

The shunt reactors (SR) are designed to be connected to the endpoints of high-voltage cables or to the high-voltage transmission lines with the intention of regulating the line voltage by absorbing reactive power [1]–[3]. SR can be permanently installed or switched on under light-load situations for voltage regulation solely in service. In response to the varying system load requirements, SR switching is carried out daily. However, the switching processes present serious problems, particularly when the SR is disconnected during times of heavy load. The circuit breaker (CB) usually chops the reactor current before it reaches its potential zero value when interrupting the current. This occurrence is referred to as inductive current chopping, and depending on value of chopped current, significant overvoltages will result as a consequence [4]–[7].

Calculating this overvoltage, often referred to as chopping overvoltage, requires observation of the reactor circuit's energy balance. The oscillation that results has a frequency range between 1 kHz and 5 kHz [8]. In addition to the chopping overvoltage, the interruption of the current will cause a transient recovery voltage (TRV) to occur across the CB. A CB performance as well as the configuration at the reactor location determines the magnitude of TRV. If damping is neglected, its predicted maximum value is the sum of the source's peak voltages plus the overvoltage produced by the current chopping [9]. Switching that is controlled is a technique for disposing dangerous transients through time-controlled switching operations.

Commands to close or open the CB are delayed so that contact separation or making will occur at the ideal time instant for the voltage, current, as well as phase angle [10]. With the use of controllers, energising and de-energizing processes can be managed in relation to the position of the point-on-wave, in addition to no harmful transients will be produced. The aim of controlled opening is to prevent short arcing times as they pose the greatest risk of re-ignitions or restrikes [11]. CB performance, load circumstances, and system frequency will all have an impact on the need for controlled opening. Controlled switching is possible for all kinds of SR, irrespective of the magnetic and electrical circuit. A controlled opening method involves determining arcing times that are long enough to prevent re-ignitions during de-energizing [12]. During both energization and de-energization, SR switching transients have been analyzed, as reported in [13]. In a 400 kV system, the overvoltage caused by removing a 100 Mvar reactor can reach to 2.05 p.u. if the surge arrester is not installed. The voltage steepness in an occurrence of reignition was computed to analyse the dielectric stress on the SR windings in additional to the overvoltage to ground [14].

The objective of this paper is to provide a comprehensive overview of switching transient overvoltages during a shunt reactor de-energization case and the impact of the current chopping in this condition. Additionally, switching transients generated by both controlled and uncontrolled switching of the CB are explained. The switching overvoltage across the SR is computed using two different rating of SR (50 MVAr) and (150 MVAr) in order to clarify the effect of SR rating on the transient overvoltage. The mitigation method for the switching transient has implemented through the proposed model in this study which represented by circuit modification. To achieve this work, a model of the SR and system equipment was implemented using ATP-draw software program.

2. SHUNT REACTOR RATING

The shunt reactor rating should indeed be described in terms of Mvar and rated voltage. For illustration, a three-phase shunt reactor installed on a 500 kV system might well be rated at 135 MVar at 525 kV [15]. Figure 1 illustrates how SR are often connected to electrical networks. Rated power (MVar) and rated voltage are used to describe SR ratings.

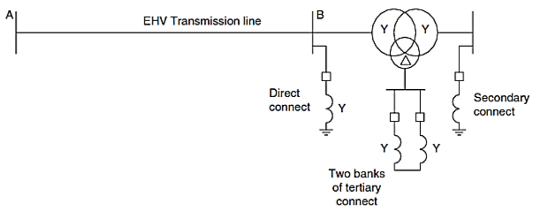


Figure 1. Typical connections of SR

SR can be installed to systems with voltages lower than 60 kV by using a power transformer's tertiary winding that is connected to the overhead transmission line being compensated. Tertiary-connected SR come in a variety of configurations, including air core, dry type, single-phase per unit or oil-immersed as well as three-phase or single-phase per unit design. SR are often directly connected to the high-voltage transmision line or busbar that needs to be compensated at system voltages of 60 kV and higher as shown in Figure 2 [8].

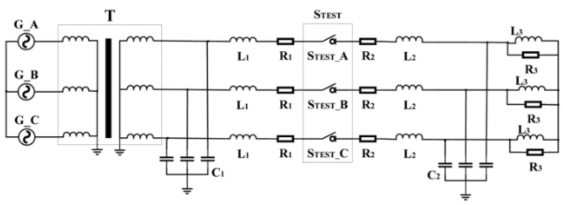


Figure 2. Shunt reactor connection

The power rating of these SR ranges from 30 to 300 MVar (three-phase). Directly connected SR are typically of the oil-immersed kind. Depending on the voltage profile, this direct connection to an overhead transmission line is performed either at the line's terminal or a middle place.

3. INTERRUPTING SHUNT REACTOR BANK

The CB normally interrupts the current at the first current zero following contact separating, but it might not be instantly able to withstand the high magnitude recovery voltages that may later arise across the contacts. This may result in re-ignition, another current loop at the rated frequency followed by a successful interruption. The equivalent single phase circuit seen in Figure 3 can be used to investigate the switching of directly grounded reactors. Fundamentally, SR current can be abruptly interrupted by CB, and this is known as “current chopping,” when the current is imposed to prematurely to zero. However, the current chopping and subsequent reignitions that follow can produce massive transient overvoltages [15]. Overvoltages of the two types that follow are produced: i) chopping overvoltages and ii) reignition overvoltages. Two additional CB features may have a considerable impact on the switching process: i) increasing the contact gap’s dielectric withstand after an interruption, which affects the possibility that re-ignitions may occur and ii) the ability to disconnect high-frequency currents following re-ignitions, which affects the possibility of multiple re-ignitions and voltage escalation.

On the CB and connected system, a specific and severe duty is imposed due to SR switching. The current that must be interrupted at high voltages is typically less than 300 A, but effective interruption depends on a complicated interaction among both the CB and the circuit. Small inductive currents are the general term used to describe the load currents of SR [16]. Typically, it is not a concern for CB to be capable to interrupt low inductive currents.

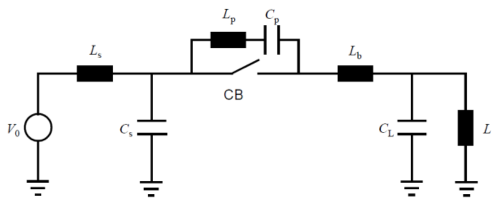


Figure 3. Shunt reactor switching analysis using a single-phase equivalent circuit [15]

Where Ls is the load side inductance, CB is the circuit breaker, Cs is the source side capacitance, Lb is the connection series inductance, CL is the shunt reactor stray capacitance, Lp and Cp are the breaker stray inductance and capacitance.

4. EFFECT OF CURRENT CHOPPING OCCURRENCE

Due to the possibility of current chopping and the subsequent switching overvoltage, it was once considered to be harmful to disconnect small reactive current. In addition, the propensity of the CB to chop reactor current is not as strong for normal high voltage (HV) SR rated current values, hence modern surge arresters are completely able to handle this circumstance. Current instability and a fast increase in the current magnitude are activated by the abrupt opening of the CB, which results in current chopping. For the purpose of preventing the influence of overvoltage as a consequence of the current chopping, the SR is typically de-energized when the current is zero. To investigate the chopping number, which shows the characteristics of the CB in every type as well as the total capacitance in parallel with the breaker as (1), the case of switching a CB to open a SR has been used [15], [17].

$$I_{ch} = \lambda\sqrt{C_t} \tag{1}$$

Where λ is chopping number $[A\cdot F]^{-0.5}$, C is total capacitance seen from the CB terminals [F].

As stated, only CB with a single chamber is covered (1). The following equation applies to CB having N chambers units per pole [15].

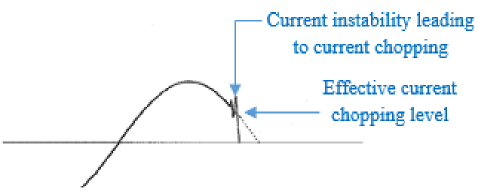
$$I_{ch} = \lambda\sqrt{NC_t} \tag{2}$$

According to different types of quenching medium, the chopping number λ could be considered of as a CB characteristic constant (with the exception of vacuum CB). Table 1 provides typical λ constants for SF6, air blast, and minimum oil CB. Boundary values have to be given because the chopping number had not been clearly stated. In (1) uses the equivalent capacitance C to account for how the system characteristics affect the chopping current value [17].

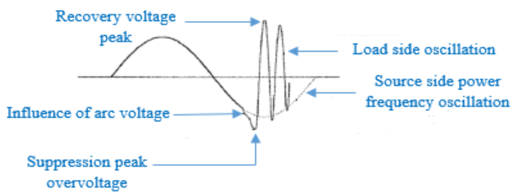
Table 1. Chopping numbers on some kinds of CB [15]

CB type	Chopping number $AF^{-0.5}$
Minimum oil	$5.8 \cdot 10^4$–$10 \cdot 10^4$
Air blast	$15 \cdot 10^4$–$20 \cdot 10^4$
SF_6 puffer	$4 \cdot 10^4$–$19 \cdot 10^4$
SF_6 self-blast	$3 \cdot 10^4$–$10 \cdot 10^4$
SF_6 rotating arc	$0.39 \cdot 10^4$–$0.77 \cdot 10^4$

The value of λ is often dependent on the period of the arc for CB. The statistics average of the variable λ can be employed if the relationship between it and the arc period is not obviously linear. According to Bhatt *et al*. [10], the typical values of λ for high voltage CB having various arc-extinction medium range from 0.39 10^4 to 20 10^4 $AF^{0.5}$ [12]. Overvoltages are produced as a result of the current-chopping phenomena, also known as current suppression. A straightforward example of current chopping and its related overvoltage across the shunt reactor is shown in Figure 4. Figure 4(a) shows stands for the circuit breaker's current chopping, and Figure 4(b) shows indicates the transient overvoltage across the shunt reactor, where the current is abruptly stopped before it naturally crosses the point of zero. Figure 5 shows the moment which the current is forced to the zero value before its natural zero crossing [18].



(a)



(b)

Figure 4. Overvoltage caused by current chopping: (a) current across breaker and (b) voltage through reactor

When the current is abruptly interrupted occurs, the voltage is almost at its maximal value because the circuit is mostly inductive in nature. When current chopping happens, a considerable magnitude of energy is trapped on the reactor [19]. Figure 6 demonstrate that when an immediate disconnected current happens, the load side's overvoltage is obtained. It is possible to determine the suppression peak overvoltage (Vma) or the chopping overvoltage from the energy balance shown in (2) [20].

$$\frac{1}{2}CV^2 = \frac{1}{2}LI_{ch}^2 + \frac{1}{2}CV_O^2 \quad (3)$$

Where in (2) provides the extinction peak overvoltage to reactor voltage ratio in pu form (3).

$$\frac{V}{V_O} = \sqrt{(1 + \frac{LI_{ch}^2}{CV_O^2}} \quad (4)$$

Where $u(t)$ is voltage, $i(t)$ is current, I_N is nominal current peak, i_{ch} is chopping current, U_p is peak voltage after de-energization, U_N is nominal phase voltage, f_0 is frequency of oscillations [17].

Modern puffer type SF6 CB rarely reignite during the suppression peak overvoltage loop and have modest chopping levels of 5-10 A. Depending on the parallel capacitance of the circuits, air blast breakers can chop inductive load currents of 50 A or above, but they are susceptible to multiple reignition overvoltages [21]. It is observed that when disconnecting a low inductive current related with disconnection of the SR, an instantly produced TRV tends to activate residual electrons and it may cause the reignition between the CB contacts [22]. A CB's TRV is the point-by-point differential in voltage between its incoming and outgoing sides. The connected side of the bus or supply, or the incoming side, tries to restore power frequency voltage level and when a CB interrupts, the outgoing side oscillates as well, depending on what is connected. Recovery voltage is the difference between these voltages [17]. Figure 7 illustrates re-ignition concept diagram.

TRV and insulation recovery characteristics of the fracture medium have the greatest effects on re-ignition. The fracture's dynamic dielectric strength exhibits some dispersion, and as a result, the arc's re-ignition exhibits some randomly. As the re-ignition proceeds, the overvoltage will increase, potentially damaging additional system components [23]. Any type of CB can re-ignite, and this is not absolutely prevented. Regardless of the switching mechanism, the re-ignition overvoltage could occur when the reactor is disconnected if there is no particular voltage suppression measure in place. Figure 8 illustrates the effect of arcing time on the dielectric strength and as a consequence the possibility for occurrence of re-ignition.

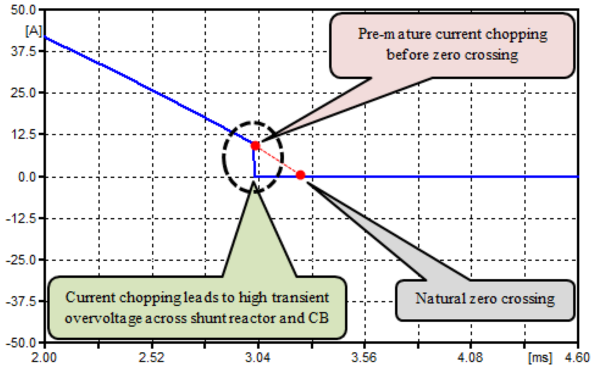


Figure 5. Current chopping instant

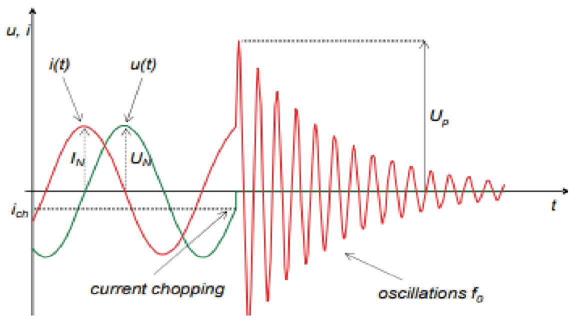


Figure 6. Inductive current interruption without arc re-ignition

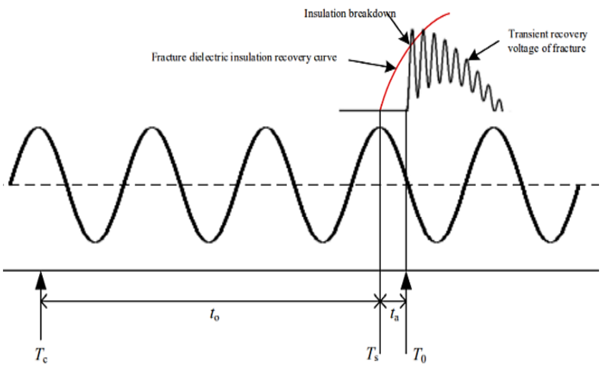


Figure 7. Re-ignition mechanismdiagram [23]

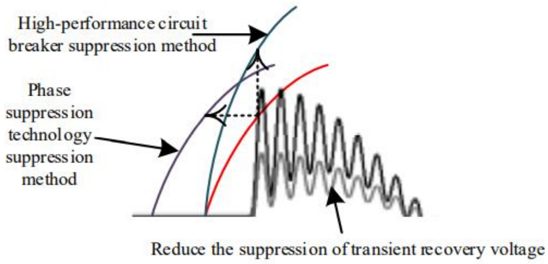


Figure 8. Extend the use of arcing time (t_a) phase control technologies [23]

The intersection of the fracture TRV and the fracture dielectric insulation recovery curve is the primary cause of re-ignition. As a result, as seen in Figure 8, the concept of preventing or minimizing re-ignition may be divided into three categories. When the CB's dielectric insulation recovery curve and the fracture TRV is tangent, a space known as the "re-ignition window" is created between the associated arcing time and the zero-crossing point T_0. The configuration at the reactor location as well as the effectiveness of the CB determines how much TRV will be generated. Its expected maximum value is equal, if damping is not taken into consideration, to the summation of the peak voltages of the source plus the excess voltage produced by current chopping. Taking the viewpoint that the maximum acceptable voltage across the CB must not exceed than 80% or 2.43 p.u [15].

5. ANALYTICAL MODEL FOR REACTOR SWITCHING

An ATP-draw component three-phase AC source is used to depict the supply network in Figure 9. As shown in Table 2, other factors taken into account include the source's internal impedance as well as the surge impedance visible from the reactor terminal. The CB is modeled by a time-controlled switch with a chopping level of 20 A for each pole. This model is considered to be the simplest substitute for breaker modeling and could be used to represent both the SF6-insulated and air-blast type breakers. Finally, to demonstrate how the SR rating affects transient overvoltages, two simples SR (50 MVAr and 150 MVAr) with an inductor and capacitor connected in parallel are used.

Along with the previously described mitigation techniques. This study proposed a different strategy for reducing transient overvoltage. The circuit shown in Figure 9 can be modified to implement the proposed technique, where it was described by adding CB_2 with its resistance and connecting it parallel to the SR terminals. Figure 10 presents the circuit diagram after modifications. This technique aims to close CB_2, simultaneously when CB_1 is opened. The idea behind the suggested approach is to use CB_2 and its resistance to absorb transient overvoltages that occur during SR de-energisation.

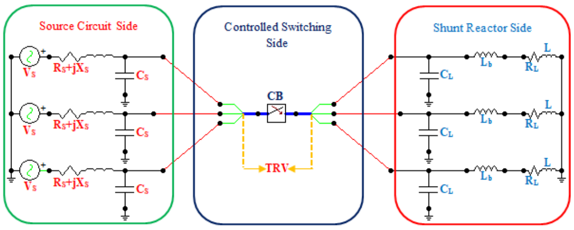


Figure 9. Shunt reactor's equivalent ATP-draw model

Table 2. Parameters of the reactor [24], [25]

Parameter	Value	Unit
Source side parameters		
Equivalent source resistance (Rs)	0.77	Ω/phase
Equivalent source impedance (X_L)	6.19	Ω/phase
Stray capacitance on the source side (Cs)	4	nF/phase
SR parameter with rating of (50 MVAr)		
Stray capacitance on the load side (C_L)	8.2	nF/phase
Equivalent resistance of reactor (R_L)	8.6	Ω/phase
Inductance of reactor (L)	9.92	H/phase
SR parameter with rating of (150 MVAr)		
Bus inductance (L_B)	32	µH/phase
Stray capacitance on the load side (C_L)	3.2	nF/phase
Equivalent resistance of reactor (R_L)	1.2	Ω/phase
Inductance of reactor (L)	3.395	H/phase

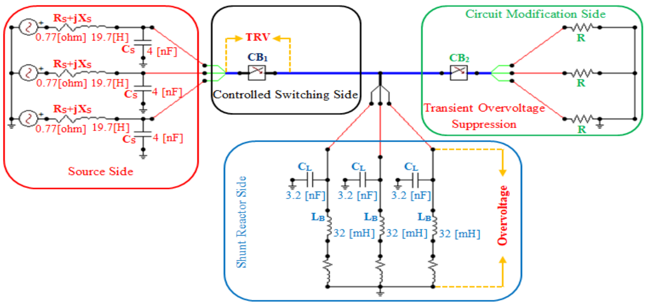


Figure 10. Circuit diagram after modification

6. RESULTS AND DISCUSSION

This part of the paper includes the results of the switching transient case, as it is centered on two main parts, the first is the results that included the case of uncontrolled switching and the second is the results that included the case of controlled switching. Both cases have applied for different rating of shunt reactor. The results will be discussed in detail in this section.

6.1. Uncontrolled switching

The following section presents the voltage responses of the SR as well as the CB during the worst-case de-energizing transient. The highest value of the reactor current corresponds to the instant at which the switching time was selected. The estimated SR voltage for this situation is shown in Figures 11 and 12. Unfavorable conditions at the moment of opening cause high produced overvoltages on all phases of the SR, as is to be predicted. Capacitive and inductive interphase coupling can be observed.

Phase C, which was the first phase to clear, had the largest amplitude of the suppression peak overvoltage, measuring 609 kV. The second and final interrupted phases, phase A and phase B, have calculated suppression peak overvoltages of 600 kV and 607 kV, respectively. These values where considered in case of (50 MVAr) as a SR rating. The worst-case de-energizing transient at the CB is shown in Figures 13 and 14. As can be observed, all phases of the CB create voltage at approximately the same magnitudes as in the prior simulation scenario. In contrast to the preceding scenario, the peak overvoltage magnitude in this instance was slightly lower and was seen on phase C. The main reason that leads to the excessive overvoltage is the high value of chopping current, which in turn leads to the release of the stored energy in the form of high voltage.

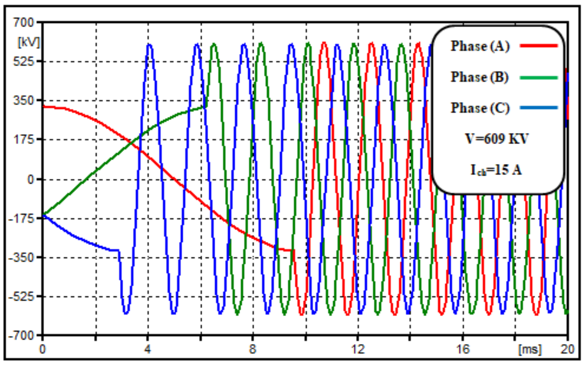


Figure 11. Overvoltage on shunt rector bank with rating of (50 MVAr)

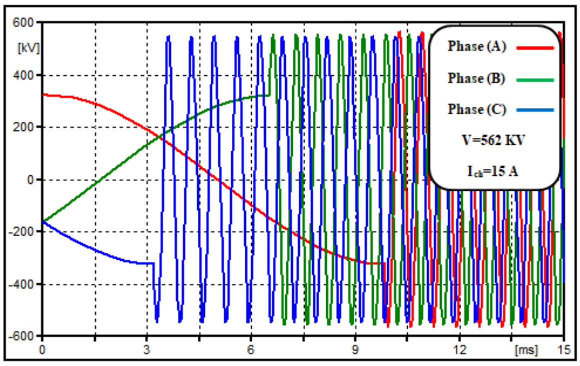


Figure 12. Overvoltage on shunt rector bank with rating of (150 MVAr)

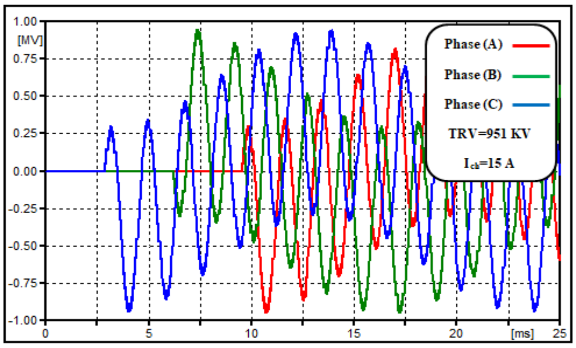


Figure 13. TRV on CB with rating of (50 MVAr)

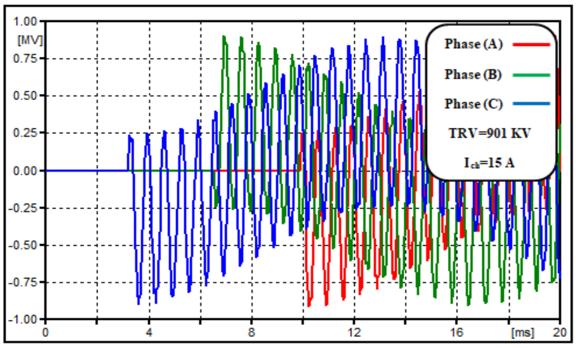


Figure 14. TRV on CB with rating of (150 MVAr)

6.2. Controlled switching

When the de-energization of the SR takes place at the exact instant that corresponds to the minimum value current chopping, the results shown are obtained. Figures 15 and 16 displays the estimated SR voltage for all phases during open operation. All phase of the SR voltage were shown in the figure and there were no overvoltages that could be noticed since the current during the disconnection on these phases were at their lowest. The working times of each pole, which in turn define the amount of the chopped current, have a significant role in determining their magnitudes.

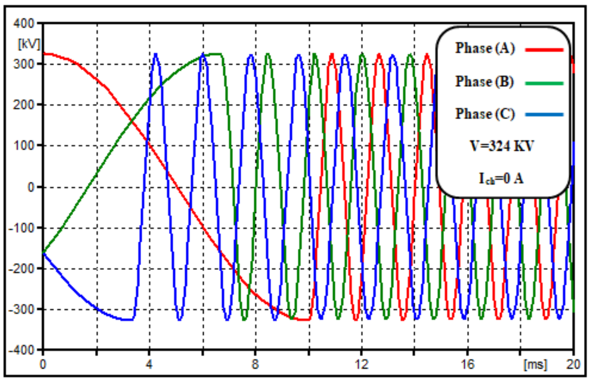


Figure 15. Overvoltage on shunt rector bank with rating of (50 MVAr)

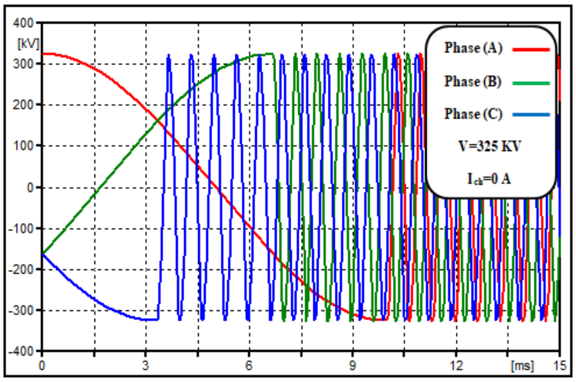


Figure 16. Overvoltage on shunt rector bank with rating of (150 MVAr)

As demonstrated in Figures 15 and 16, there was no overvoltage on any of the SR voltage's phases; however, their magnitudes were influenced by how each pole's operating time. The voltage across the CB, as represented by the TRV in Figures 17 and 18. It is noticeable in this part of the work that with the decrease in the value of the chopping current to its lowest level, it did not produce a significantly high voltage. The estimated voltage across the CB during SR disconnection has been illustrated. According to the results, there are less significant overvoltages on each of the three phases. The difference between the system voltage on source-side and load-side oscillations is represented by the stress that results. Although switching at current zero crossing is the ideal circumstance to avoid overvoltages and re-ignition, in reality, because these CB are mechanical switches, there is a delay between the moment of zero crossing and actual switching instant (approximately ± 15 deg or more). The efficiency of switching might be increased by continuously monitoring the line voltages and currents on both ends of the breaker poles and by using modern power electronics.

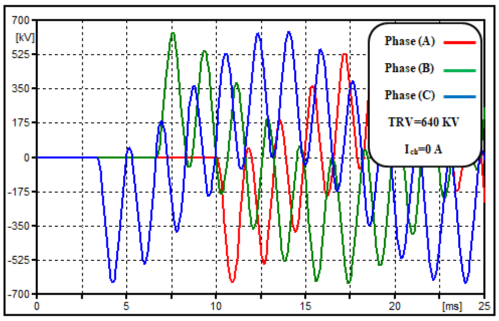


Figure 17. TRV on CB with rating of (50 MVAr)

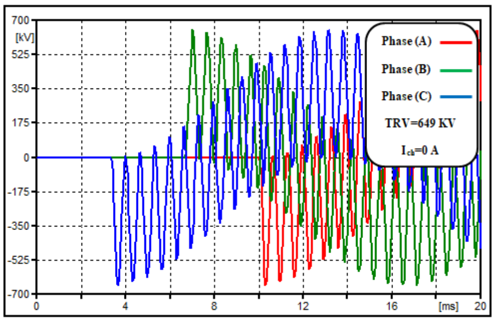


Figure 18. TRV on CB with rating of (150 MVAr)

6.3. Using of the proposed method (circuit modification)

The approach proposed in this section is more effective than conventional techniques at reducing overvoltages across the SR and TRV over the CB. Therefore, the results presented here have been categorized into two parts, part 1 presents the results of the circuit modification technique without controlled switching and part 2 presents the results of the circuit modification technique with controlled switching. This could help in highlighting the relevance of the circuit modification as a recommended approach. The overvoltages across the SR, when employing the circuit modification alone, are shown in Figures 19 and 20.

When employing the modified circuit with uncontrolled switching, Figures 21 and 22 respectively exhibit the TRV across the CB. The proposed modification to the circuit will reduce the excess transient voltages. This process was carried out with a high chopping current to show the importance of the proposed modification to the circuit in reducing the high transient overvoltages. The proposed methodology of circuit modification decreased the transient overvoltage even with significant current chopping which represents the uncontrolled switching case. The modified circuit served as an overvoltage absorber. Figures 23 to 26 represent the state of the using of circuit modification with controlled switching, that is, at the value of the chopping current I_{ch}=0 A, where the Figures 23 and 24 represent the transient overvoltage across the SR, while the Figures 25 and 26 represent TRV over the CB. Thus, no transient overvoltages were created during the de-energisation of the SR.

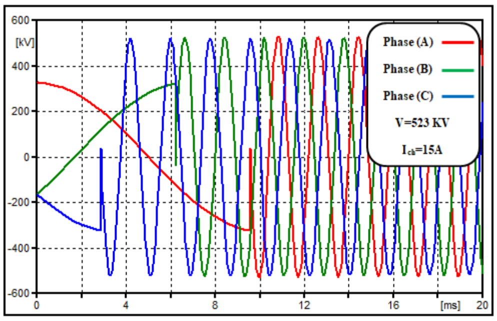


Figure 19. Overvoltage across SR using circuit modification when I_{ch}=15 A with rating of (50 MVAr)

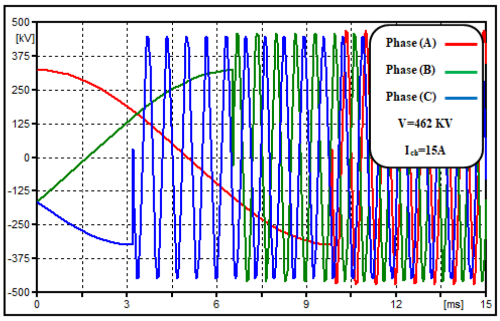


Figure 20. Overvoltage across SR using circuit modification when I_{ch}=15 A with rating of (150 MVAr)

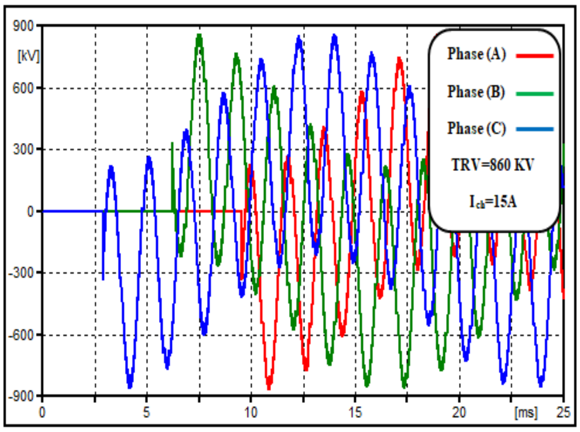


Figure 21. TRV across CB using circuit modification when I_{ch}=15 A with rating of (50 MVAr)

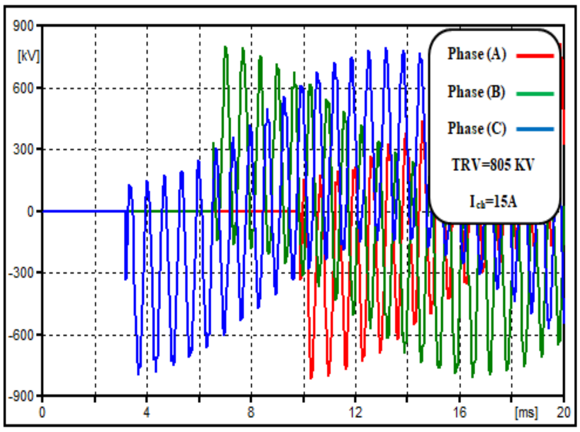


Figure 22. TRV across CB using circuit modification when I_{ch}=15 A with rating of (150 MVAr)

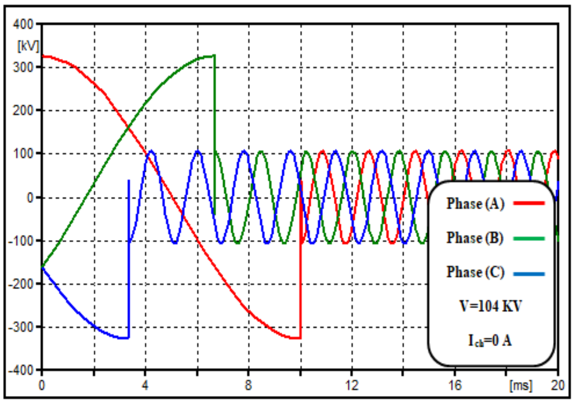


Figure 23. Overvoltage on shunt rector bank with rating of (50 MVAr)

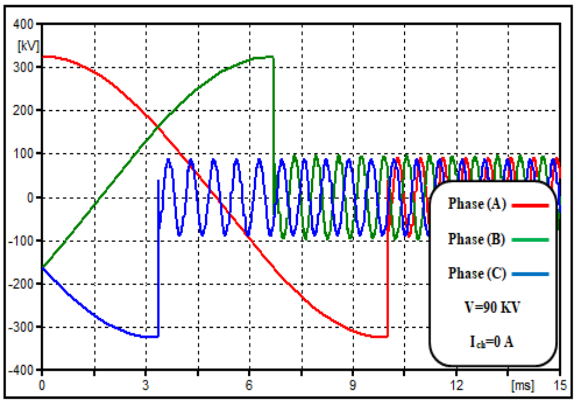


Figure 24. Overvoltage on shunt rector bank with rating of (150 MVAr)

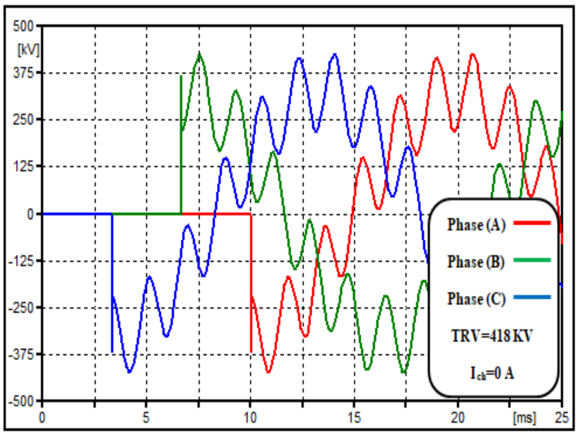


Figure 25. TRV on CB with rating of (50 MVAr)

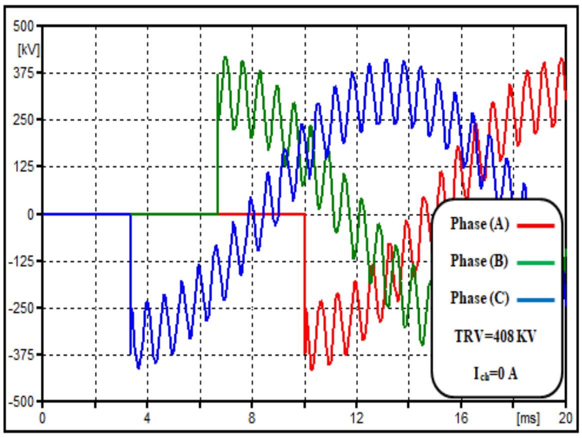


Figure 26. TRV on CB with rating of (150 MVAr)

Along with controlled switching, the proposed strategy involving circuit modification also absorbs a huge proportion of transient overvoltage across a SR and a CB. Simulations were used to examine the three-phase SR switching overvoltages during an operational substation. The disconnection of the SR was specifically evaluated at 0° and 90° on the voltage waveform of phase A, which are supposed to be the most significant instants for a comparison data of the switching overvoltages. High overvoltages are produced when the CB randomly opens.

Additionally, the effects of chopped current on overvoltage were investigated; greater chop levels result in severe overvoltages between the reactor and the CB. Switching during current zero that corresponds to the point at which the reactor has the smallest amount of energy stored can reduce these amplitudes. The results of transient overvoltage for the shunt and the CB are provided in Tables 3 and 4 for different rating of SR (50 MVAr) and (150 MVAr). Both tables include results for both before and after the proposed methods, which is represented by the circuit modification.

Table 3. Transient overvoltage results before and after circuit modification (50 MVAr)

Overvoltages and TRV													
Before circuit modification							After circuit modification						
I_{ch} (A)	Overvoltage on SR			TRV on CB			I_{ch} (A)	Overvoltage on SR			TRV on CB		
	A (kV)	B (kV)	C (kV)	S (kV)	B (kV)	C (kV)		A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)
20	755	762	760	1110	1118	1113	20	690	695	688	1008	1014	1011
15	600	607	609	951	947	944	15	523	521	518	860	858	854
12	519	524	521	855	860	858	12	415	422	417	741	745	740
10	468	473	470	797	804	800	10	348	355	352	673	680	678
7	400	398	403	725	723	729	7	251	253	255	576	572	573
5	365	364	362	687	686	684	5	193	190	186	509	507	503
3	340	338	337	659	657	658	3	143	141	135	455	453	449
0	325	325	325	640	640	640	0	104	106	107	422	420	418

Table 4. Transient overvoltage results before and after circuit modification (150 MVAr)

Overvoltages and TRV													
Before circuit modification							After circuit modification						
I_{ch} (A)	Overvoltage on SR			TRV on CB			I_{ch} (A)	Overvoltage on SR			TRV on CB		
	A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)		A (kV)	B (kV)	C (kV)	A (kV)	B (kV)	C (kV)
20	698	688	707	1037	103	1044	20	615	608	626	961	948	969
15	562	554	546	901	896	891	15	462	454	443	805	797	788
12	490	484	476	832	823	816	12	370	363	355	710	702	695
10	445	438	433	781	778	772	10	310	303	295	648	636	629
7	372	382	376	696	705	700	7	205	215	208	538	546	543
5	346	353	351	676	682	679	5	145	159	152	472	486	478
3	328	333	330	659	660	657	3	102	110	107	428	436	432
0	323	322	324	650	652	649	0	90	95	87	411	416	408

In the absence of dampening, the chopped current level (values vary from 0 to as high as 20 A or more) and the surges impedance at the reactor terminals define the phase-to-ground overvoltage magnitude. Additionally, the MVAr rating of the reactor affects how much overvoltage is generated at the shunt reactor. The simulation results have shown that the proposed model proved that the reduction of the overvoltage were 86% in case of (50 MVAr) SR rating and 87% in case of (150 MVAr) SR rating in comparison with [1] which get (71%) of suppression overvoltage.

7. CONCLUSION

The switching transients resulting by the controlled and uncontrolled switching of a three-phase 400 SR at a reactive power of (50 MVAr and 150 MVAr) are discussed in this study. A SR with a high MVAr rating has low inductance and high capacitance values for the same rated voltage. Since the surge impedance of the SR will be low as a result of this LC combination, the overvoltage magnitude will be decreased. A SR, on the other hand, has a low rated power and a comparatively large inductance as well as low capacitance values. Due to the large surge impedance present in this reactor, the overvoltage created is of a significantly higher magnitude. As recommended by IEEE C37.015 standards, the overvoltage factor in this study never exceeded 80% when employing the proposed technique, which could be represented by circuit modification. It can be seen that the proposed method limits peak values of overvoltages, caused by current chopping and reignitions to very low level that will not cause insulation damage, it is noted that even with current chopping value reached 10 A no significant overvoltage is considered.

ACKNOWLEDGEMENTS

This work was supported by Universiti Sains Malaysia, under Research University Grant Scheme (RUI) 1001/PELECT/8014127.

REFERENCES

[1] Y. Geng *et al.*, "Three-phase modeling of 40.5-kV vacuum circuit breaker switching off shunt reactors and overvoltage suppression measure analysis," *Electric Power Systems Research*, vol. 194, pp. 1–10, 2021, doi: 10.1016/j.epsr.2021.107058.
[2] F. S. B. Abdullah, M. A. M. Piah, N. A. Othman, and A. Din, "Prediction of surface leakage current of overhead insulators under environmental and electrical stresses," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 5, pp. 1747–1754, 2020, doi: 10.11591/eei.v9i5.2182.
[3] Y. L. Xin, Y. H. Yang, B. N. Zhao, L. Xu, Z. Y. Yu, and W. H. Tang, "Configuration of suppression schemes against high-frequency transient reignition overvoltages caused by shunt reactor switching-off in offshore wind farms," *International Journal of Electrical Power and Energy Systems*, vol. 141, 2022, doi: 10.1016/j.ijepes.2022.108170.
[4] R. K. Antar, M. Y. Suliman, and A. A. Saleh, "Harmonics resonance elimination technique using active static compensation circuit," *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 5, pp. 2405–2413, 2021, doi: 10.11591/eei.v10i5.3148.
[5] H. A. Hussein, H. J. Motlak, and H. N. A. Almusawi, "Effect of switched-capacitor on super-lift Luo converter," *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 6, pp. 3119–3126, 2022, doi: 10.11591/eei.v11i6.3604.
[6] A. N. Shpiganovich, A. A. Shpiganovich, and K. A. Pushnitsa, "On the applicability of the Mayr arc model for studying current chopping and overvoltages generated by low-oil current breakers," *Russian Electrical Engineering*, vol. 88, no. 6, pp. 378–380, 2017, doi: 10.3103/S1068371217060141.
[7] H. Heiermeier, "Testing of reactor switching for UHV circuit breakers," *IEEE Transactions on Power Delivery*, vol. 30, no. 3, pp. 1172–1178, 2015, doi: 10.1109/TPWRD.2015.2394238.
[8] IEEE Power and Energy Society, "IEEE Guide for the Application of Shunt Reactor Switching," *IEEE Std C37.015 (Revision of IEEE Std C37.015-1993)*, 2009.
[9] A. Xemard, B. Jurisic, M. Rioual, A. Olivier, and E. Sellin, "Interruption of small, medium-voltage transformer current with a vacuum circuit breaker," *Electric Power Systems Research*, vol. 187, pp. 1–7, 2020, doi: 10.1016/j.epsr.2020.106502.
[10] K. A. Bhatt, B. R. Bhalja, and U. Parikh, "Evaluation of controlled energization of shunt reactors for minimizing asymmetric DC component of charging current with circuit breaker having pre-insertion resistors," *International Journal of Electrical Power and Energy Systems*, vol. 93, pp. 340–351, 2017, doi: 10.1016/j.ijepes.2017.06.009.
[11] M. A. Al-Tak, M. F. Bin Ain, O. S. Al-Yozbaky, and M. K. M. Jamil, "Impact of Shunt Reactor Overvoltages Switching in High Voltage System," *8th International Conference on Engineering and Emerging Technologies, ICEET 2022*, 2022, pp. 1–6, doi: 10.1109/ICEET56468.2022.10007338.
[12] M. I. Aleksandrova, V. A. Naumov, V. I. Antonov, and N. G. Ivanov, "Optimal Conditions for Controlled Switching of a Three-Phase Shunt Reactor," *Power Technology and Engineering*, vol. 54, no. 3, pp. 438–443, 2020, doi: 10.1007/s10749-020-01229-4.
[13] I. Ugleši and S. Hutter, "Transients Due to Switching of 400Shunt Reactor," *International Conference on Power System Transients (Brazil)*, no. 1, 2001.
[14] A. H. Khavari, A. Munir, and Z. Abdul-Malek, "Circuit-based method for extracting the resistive leakage current of metal oxide surge arrester," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 6, pp. 2213–2221, 2020, doi: 10.11591/eei.v9i6.2258.
[15] IEEE Power and Energy Society, "IEEE Guide for the Application of Shunt Reactor Switching," *IEEE Std C37.015 (Revision of IEEE Std C37.015-2009)*, 2018.
[16] B. Filipović-Grčić *et al.*, "Monitoring of transient overvoltages on the power transformers and shunt reactors - Field experience in the Croatian power transmission system," *Procedia Engineering*, vol. 202, pp. 29–42, 2017, doi: 10.1016/j.proeng.2017.09.692.
[17] P. Oramus, T. Chmielewski, T. Kuczek, W. Piasecki, and M. Szewczyk, "Transient recovery voltage analysis for various current breaking mathematical models: Shunt reactor and capacitor bank de-energization study," *Archives of Electrical Engineering*, vol. 64, no. 3, pp. 441–458, 2015, doi: 10.2478/aee-2015-0034.
[18] British Standards Institution., "ICE 60071-4:2004 - Insulation co-ordination - Part 4:Computational guide to insulation co-ordination and modelling of electrical networks," p. 60071, 2004.
[19] T. Chmielewski, P. Oramus, M. Szewczyk, T. Kuczek, and W. Piasecki, "Circuit breaker models for simulations of short-circuit current breaking and slow-front overvoltages in HV systems," *Electric Power Systems Research*, vol. 143, pp. 174–181, 2017, doi: 10.1016/j.epsr.2016.10.046.
[20] K. Limtrakul, S. Premrudeepreechacharn, and Y. Baghzouz, "Analysis of replacement from disconnecting switch to circuit breaker for 500 kV line shunt reactor," *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, vol. 2018-May, pp. 1–6, 2018, doi: 10.1109/ICHQP.2018.8378944.
[21] IEEE Power Engineering Society, "IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Rated Over 500 kVA," *IEEE Std C57.21^{TM}-2008 (Revision of IEEE Std C57.21-1990)*, 2008.
[22] R. Arranz, A. Rodríguez, and F. Muñoz, "Detection of the natural frequency of transmission power lines applying S-transform on Transient Recovery Voltage," *Electric Power Systems Research*, vol. 182, 2020, doi: 10.1016/j.epsr.2019.106142.
[23] B. Yu, G. Yu, Y. Zheng, L. Zhou, and C. Li, "Research on switching overvoltage suppression of 35shunt reactor," *Journal of Physics: Conference Series*, vol. 1633, no. 1, 2020, doi: 10.1088/1742-6596/1633/1/012095.
[24] M. Sonagra, U. Parikh, and V. Upadhyay, "Controlled Switching of Non-coupled & Coupled Reactor for Re-ignition free De-energization Operation," *2019 IEEE 5th International Conference for Convergence in Technology, I2CT 2019*, 2019, doi: 10.1109/I2CT45611.2019.9033675.
[25] A. Barghandan and B. Sedaghat, "Simulation of switching overvoltages of 400shunt reactor," *Transformers Magazine*, vol. 2, no. 1, pp. 50–59, 2015.

BIOGRAPHIES OF AUTHORS

Mazyed A. Al-Tak is currently a Ph.D. student, at the School of Electrical and Electronic Engineering, University Science Malaysia (USM), Malaysia since 2020; and he has been a lecturer since 2017. He received the B.Eng. degree in Electrical Engineering from College of Department Engineering Electrical, University of Mosul in 2006 and the M.Eng. degree in Power System, from University Malaysia Perlis UniMap, in 2014. He started his work at the University of Mosul, Iraq since 2006. He can be contacted at email: mazyed.altak@uomosul.edu.iq.

Mohd Fadzil Ain received the B.S. degree in Electronic Engineering from Universiti Teknologi Malaysia, Malaysia, in 1997, the M.S. degree in Radio Frequency and Microwave from Universiti Sains Malaysia (USM), Malaysia, in 1999, and the Ph.D. degree in Radio Frequency and Microwave from the University of Birmingham, U.K., in 2003. In 2003, he joined the School of Electrical and Electronic Engineering, USM. He is currently a Professor with VK7 grade, the Dean of Research, Postgraduate and Networking, and the Director of Collaborative Microelectronic Design Excellence Centre (CEDEC). He is actively involved in technical consultancy with several companies in repairing microwave equipment. His current research interests include MIMO wireless system on FPGA/DSP, Ka-band transceiver design, dielectric antenna, RF characterization of dielectric material, and microwave propagation study. His awards and honors include International Invention Innovation Industrial Design and Technology Exhibition, International Exposition of Research and Inventions of Institutions of Higher Leaning, Malaysia Technology Expo, Malaysian Association of Research Scientists, Seoul International Invention Fair, iENA, Best Paper for the 7th WSEAS International Conference on Data Networks, Communications, Computers, and International Conference on X-Ray and related techniques in research and industry. He can be contacted at email: eemfadzil@usm.my.

Omar Sh. Al-Yozbaky he obtained his Bachelor of Science (B.Sc.) in Electrical Engineering in 2001 from the Department Electrical Engineering, College of Engineering, University of Mosul, Iraq. Then he was appointed as an assistant engineer in the same mentioned department. After that, he got M.Sc. in "overcome the effect of critical distance in xlpe high voltage cables by inductive shunt compensator", 2008 from the same mentioned department as well. Upon his graduation, he was appointed as teaching staff (assistant lecturer) in the Department of Electrical Engineering, College of Engineering, University of Mosul. In 2012, he obtained the scientific title (lecturer) and the Ph.D. degree in the Department of Electrical and Electronic Engineering, Faculty of Engineering, University Putra Malaysia in 2017. Since 2014, he was a member of the Centre for Electromagnetic and Lightning Protection Research (CELP). Now, he is assistant professor Department of Electrical Engineering, College of Engineering, University of Mosul, Iraq. The subjects for interest, renewable energy fields associated with the smart grid, thermal modeling transformer design, and electrical machines. He can be contacted at email: o.yehya@uomosul.edu.iq.

Mohamad Kamarol Mohd Jamil (senior member, IEEE) received the B.Eng. degree (Hons.) in Electrical Engineering from Universiti Teknologi Mara, Malaysia, in 2000, and the M.Eng. and D.Eng. degrees from the Kyusyu Institute of Technology, Japan, in 2005 and 2008, respectively. He joined the Universiti Sains Malaysia (USM) with a University ASTS Fellowship, in 2002, where he was a Senior Lecturer, in 2008, and was promoted to an Associate Professor, in 2014. From 2013 to 2014, he was a Visiting Researcher with the High Voltage Laboratory, Kyushu Institute of Technology, Japan. He is also involved in temperature rise and short-circuit electromagnetic study of busbar system and HVDC system. His research interests include insulation properties in oil palm, solid dielectric material, insulation properties of environmentally benign gas, and PD detection technique for insulation diagnosis of power apparatus and electrical machine. He is a member of IET, the Board of Engineering Malaysia, and the Institute Engineering Malaysia. He received the Chatterton Young Investigator Award from the IEEE International Symposia on Discharge and Electrical Insulation in Vacuum (ISDEIV), in 2006. He is a professional engineer and a chartered engineer. He can be contacted at email: eekamarol@usm.my.