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A novel method of overvoltage suppression due to de-energization of shunt reactor in high voltage system

Mazyed A. Al-Tak[1,2], Mohd Fadzil bin Ain[1], Omar Sh. Al-Yozbaky[3], Mohamad Kamarol Mohd Jamil[1]
[1]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Penang, Malaysia
[2]Computer Center, University of Mosul, Mosul, Iraq
[3]Department of Electrical Engineering, College of Engineering, University of Mosul, Mosul, Iraq

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ABSTRACT

Substations usually employ shunt reactors to reduce the reactive power of systems. Due to current chopping when the shunt reactor is shut off, a high frequency and amplitude overvoltage is generated. This study was aimed at eliminating switching-related overvoltage in shunt reactors so as to maintain the equipment, prevent insulation failure, and avoid reignition. Therefore, the circuit was modified according to the suggested mitigation strategy to verify that transient overvoltages are suppressed by the circuit breaker and shunt reactor. With a view to evaluate the existing chopping caused by the switching of reactor bank, the alternative transient's program (ATP-Draw) model was used to simulate the transients resulting from switching a shunt reactor. This work has been put into practice for various current chopping values. The collected results of the simulation showed that the proposed model was significantly highlighted for the suppression of overvoltages, with the voltage across the circuit breaker being reduced from 679 KV to 478 KV at a current chopping value of 5 A and from 351 KV to 152 KV across the shunt reactor.

Corresponding Author:

Mohd Fadzil bin Ain
School of Electrical and Electronic Engineering, Universiti Sains Malaysia
11700 Gelugor, Penang, Malaysia
Email: mazyed.altak@uomosul.edu.iq

1. INTRODUCTION

The challenge of controlling system voltage has expanded dramatically with the advent of high voltage, huge capacity, in addition to long-distance transmission technologies. Shunt reactors (SR) are employed often in high voltage systems and for high voltage transmission lines in order to control reactive power [1]–[3]. Overvoltages are caused by the excess reactive power, which is always capacitive and is produced when there is charging current and line capacitances [4], [5]. As a result of current chopping, which occurs while low inductive currents are interrupted, significant stress might be imposed on the equipment and its circuit breaker as soon as de-energizing the (SR). If the peak amplitude of the switching overvoltage is greater than the maximum switching impulse which can withstand the (SR) voltage, the equipment might be at jeopardy [6], [7]. Surge arresters protect (SRs) that are connected to their terminals. Therefore, overvoltages that result from de-energization are improbable to result in the breakdown of insulation for shunt reactors [8]–[10]. The switching responsibility is more severe if there are one or more reignitions. Shunt reactors will present considerable transient overvoltages due to such voltage breakdowns, with front times varying from a few to several microseconds, as well as being variably distributed along the winding of the (SR). Because these steep-fronted transient voltages result in substantial inter-turn overvoltages, particular emphasis will be placed on the entrance turns. To decrease overvoltages as well as the chance of the circuit breaker (CB) reigniting, several mitigating actions must be implemented. Thermic and dielectric stress caused by uncontrolled switching as a result of any of the aforementioned problems shortens the equipment's usable life. Switching transients, in addition to causing problems with power quality and dielectric and thermal deterioration, may also cause connected protective systems to malfunction [11]. To reduce the switching transients, classical preventive measures, such as surge arresters, pre-insertion resistors, or damping reactors that could be employed [12]. To withstand the dielectric stresses, the system and equipment's insulation can also be strengthened. However, these solutions might not treat the underlying source of the problem, and they might also be inefficient, expensive, or unreliable [13].

Controlled switching is the process of removing undesirable transients through time-controlled switching techniques [14]. Delay of the orders to open or close the (CB) ensures that switching occurs at the ideal time for the voltage phase angle [15]. Controlled switching is a common and inexpensive method of using a closing resistor to reduce switching surges. Since the late 1990s, there has been a significant rise in installations employing controlled switching due to excellent service performance [16], [17]. Presently, controlled switching is frequently advised for shunt capacitors and (SRs) due to its ability to offer a range of economic advantages, including the reduction of closing resistors, as well as an expansion of the maintenance interval for the nozzle and contacts of (CBs). Furthermore, it offers a number of technical advantages, including enhanced power quality, as well as the reduction of transients in distribution and transmission systems.

In this paper the explanations of the transients resulting from the switching of a three-phase 400-KV shunt reactor have adopted. Objective behind the simulations was to establish useful results to examine the significant overvoltages through the (SR) and the potential reasons for (CB) failures. Therefore, two prospects were taken into consideration: i) uncontrolled opening of the (SR) and ii) controlled opening of the (SR). Both cases were simulated with and without the proposed model represented by circuit modifications to illustrate the variations in the results. To implement this work, a model of the (SR) and system equipment was implemented using ATP-Draw software program.

2. DE-ENERGISATION OF OF SHUNT REACTOR BANK (OVERVIEW)

As a result of current chopping, which occurs during the interruption of low inductive currents, the disconnection of the (SR) may impose significant restrictions on both the (SR) and its (CB) [18]. If the maximum value of the switching overvoltage is greater than the maximum switching impulse which can withstand the shunt reactor voltage, the equipment may be at risk. However, since surge arresters protect (SRs) that are connected to their terminals, the overvoltages generated by de-energization are improbable to result in insulation failure in the (SR). The switching responsibility gets more severe when there are one or more reignitions. With front times ranging from a few microseconds to less than one microsecond, such voltage breakdowns produce severe transient overvoltages on the winding of the shunt reactor that may be unevenly distributed. The entry turns will be particularly stressed for the reason that notable inter-turn overvoltages brought on by the steep-fronted transient voltages. To reduce the eventuality of the reignition of the (CBs) and chopping overvoltages, several mitigating steps have to be taken [13]. The reactor, (CB), and system bus stray capacitances are indicated in Figure 1, which shows the circuit design for switching the reactor bank.

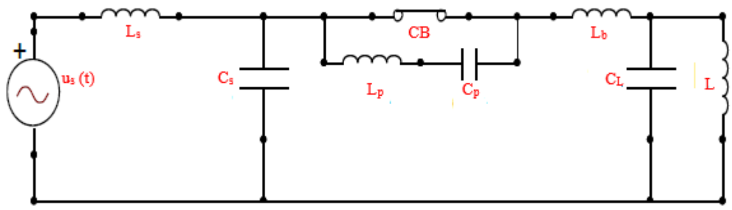

Figure 1. Shunt reactor switching analysis using a single-phase equivalent circuit [18]

Where L_S is the load side inductance, CB is the circuit breaker, C_S is the source side capacitance, L_b is the connection series inductance, C_L is the shunt reactor stray capacitance, L_P; C_P is the breaker stray inductance and capacitance, and L is the shunt reactor inductance.

$$u_s(t) = U_m \sin(w_0 t + \varphi) \tag{1}$$

Where ω_0 is the power frequency angle frequency and φ is the voltage phase angle at t = 0. During the closed state of the CB, the reactor's voltage $u_L(t)$ and current $i_L(t)$ are, respectively [19]:

$$u_L(t) = U_m \sin(\omega_0\, t + \varphi) \tag{2}$$

$$i_L(t) = \frac{1}{L}\int u_L(t)dt = \frac{U_m}{\omega_0 L}\cos(\omega_0\, t + \varphi) \tag{3}$$

at t = 0, on the reactor side, the current and the voltage are as follows:

$$u_L(t) = -\frac{U_m\omega}{\omega_0 L}\cos\varphi \sin\omega t \tag{4}$$

$$i_L(t) = \frac{U_m}{\omega_0 L}\cos\omega t \tag{5}$$

Where, $\omega = (LC)^{-1/2}$ is the reactor side circuit's angular frequency following opening, which is dependent on the stray capacitance C and reactor inductance L. consequently, the transient recovery voltage (TRV) for the (CB) is:

$$u_{TRV}(t) = \frac{U_m\omega}{\omega_0 L}\cos\varphi \sin\omega t + U_m \sin(\omega_0\, t + \varphi) \tag{6}$$

It is clear from in (2), (3), (4) and (5) that the (SR) side circuit angle frequency and the voltage phase angle have an important effect on the (CB) recovery voltage and the operational overvoltage. Chopping overvoltage's are caused by the current chopping phenomenon, also known as current suppression. A straightforward example of current chopping is illustrated by Figure 2, where the current is abruptly interrupted before it naturally crosses the zero point [20]. The voltage is close to its highest value at this point since the circuit is predominantly inductive in nature. When current chopping occurs, a large quantity of energy is trapped in the reactor [18]. According to field testing conducted on existing 400-kV switchyards with comparable circuit breakers and reactors, the chopping current values will normally vary from 2 to 14 A [21].

For iron-core reactors, the load side oscillation generated is in the order of a few kHz, while for air-core reactors, it can reach 100 kHz. The equivalent single-phase circuit illustrated in Figure 1 can be used to investigate the switching process of directly grounded reactors. In general, shunt reactor current can easily be interrupted by circuit breakers; in fact, current chopping happens when the current is abruptly forced to zero. However, the current chopping and probable re-ignitions that follow can produce significant transient overvoltages. There are two different kinds of overvoltage's that can occur: i) Chopping overvoltages with frequencies up to 5 kHz; and ii) Re-ignition overvoltages with frequencies up to several hundred kilohertz (kHz).

In (7) shows that the energy stored and the chopping voltage will increase as the chopped current level increases. Additionally, it is obvious that current chopping will have a greater impact on a reactor with a low stray capacitance [20]. The suppression peak overvoltage or chopping overvoltage may be computed using the energy balance equation illustrated below [22].

According to the energy balance formula current energy interruptions = energy at chopping peak voltage.

$$\frac{1}{2}CV^2 = \frac{1}{2}LI_{ch}^2 + \frac{1}{2}CV_O^2 \tag{7}$$

Where: C is the capacitance on the load side, I_{ch} is the current chopped level, V is the maximum chopping voltage and Vo is the peak voltage across the inductor when the current is interrupted. After rearranging the preceding equation, a new equation that provides the amount of the suppression peak overvoltage is given:

$$\frac{V}{V_O} = \sqrt{(1 + \frac{LI_{ch}^2}{CV_O^2}} \tag{8}$$

In (6) is calculated under the assumption that the arc voltage of the (CB) before current chopping is negligible [22]. Now, it is straightforward to evaluate the actual chopping current I_{ch}, from the measured overvoltage factor Ka, by using (9):

$$k_a = \sqrt{1 + \frac{3\times i^2\ ch}{2\times w\times Ct\ Q}}\, p.u \tag{9}$$

where Ct is the shunt reactor capacitance, I_{ch} is the represents the chopping currents and Q is the reactive power.

As soon as the CB contacts open at each interruption, an arc will arise between the two contacts, and it continues until reaching the zero point, where current flows in an environment of ionized gas continuously between the contacts of the circuit breaker. and as a result, after switching off, it will create varying voltages and high-frequency components, which are known as (TRV), will be generated between the two electrodes of the CB [23]–[25]. Depending on the nature of the power system's response, it can be (TRV) exponential (extra damped) or fluctuating (underdamped). There are three basic characteristics that distinguish high-frequency TRV, which are the rate of rise of the recovery voltage (RRRV), as it is known as the highest slope of the recovery voltage, the frequency of oscillation and the DC offset. If the rating of (CB) is less than the characteristics mentioned in the power system, the high (TRV) will return the arc to the interrupt moderator side [23]. It should be clear that the withstand voltage capacity raises with the contact gap distance. The voltage race theory states that the arc can be successfully extinguished if the rate of rise in dielectric strength (RRDS) is greater than the (TRV). This necessary distance is provided by a controlled switching mechanism that regulates the opening moment of the current wave [26]. According to recommendations [18], [27], 80% of the maximum value of the switching surge withstand voltage, or 3.63 p.u., is the upper limit for the switching overvoltages that can be produced by current hopping between (CB) contacts. Figure 3 shows definite evidence of current chopping.

To avoid re-ignitions in the (CB), the (TRV) fed to the device after current extinction must be lower than the dynamic withstand voltage of the (CB) dielectric during an opening operation. The TRV level is raised by current chopping. In considering this, it is possible that the high frequency TRV will cause the breaker to re-ignite if the dielectric strength between the breaker contacts is insufficient at the moment of arc extinction. If a re-ignition takes place at this point, in the process of high oscillation, the load side voltage will incline toward the source side voltage, resulting in a re-ignition overvoltage [8].

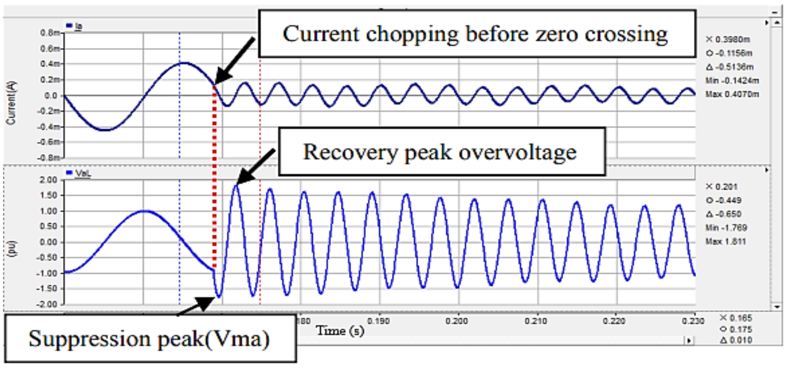

Figure 2. Overvoltage on shunt reactor caused by current chopping

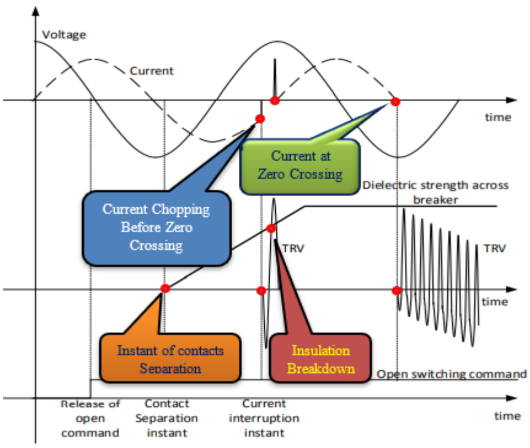

Figure 3. Reignition in a (CB) as a result of the current chopping [28]

This stress on the (CB) follows the interruption of the low inductive current by an oscillation peak on the load side voltage and a peak on the source side voltage. Typically, this is the case during the recovery voltage peak, which is the second peak of the load side oscillation [29], [30]. The re-ignition criterion was introduced to simulate the three-phase open overvoltage brought on by the first open phase re-ignition. The re-ignition occurred when $U_{TRV}>U_b$, or when the fracture recovery voltage exceeded the insulation recovery strength. A line with a slope of RRDS, or the rate of increase in insulation strength may be used to represent the relation between the insulation recovery strength and time [19]:

$$U_b\,(t) = RRDS(t - t_0) \tag{10}$$

where: (RRDS) is the rate of rise dielectric strength, and t_0 is the action time of the circuit breaker.

In order to have more understanding about re-ignition prevention cases, inductors used for voltage regulation and compensation of transmission lines are devices that oppose to current change. Due to this phenomenon, the AC voltage leads the current by 90° electrical degrees as illustrated in Figure 4. In other words, when the reactor voltage is at its crest, its current is equal to zero. Inversely, when the current is at crest, its terminal voltage is equal to 0. This means that to eliminate switching transients, the best electrical closing and opening instants are when the voltage is at its crest. Figure 5 illustrates the re-ignition of a Wye-grounded shunt reactor occurring during the (CB) opening.

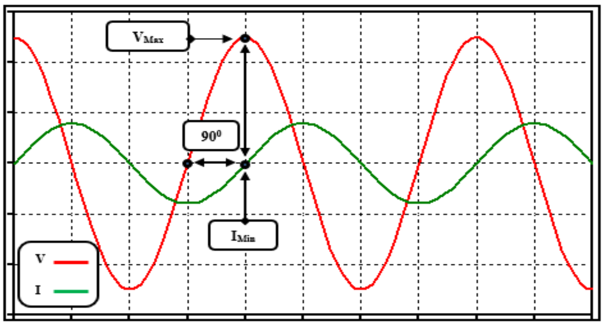

Figure 4. Current/voltage relationship in a shunt reactor

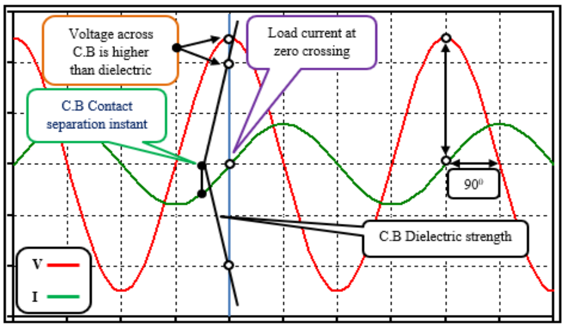

Figure 5. Clarification of the effect of arcing time due to contact separation

Reignition occurs if the (CB) contacts separation occurs too close to the zero crossing of the current: i) As soon as the contact separates, an arc is formed; ii) In the (CBs), current will continue flowing by arc because the (CB) current chopping capability is not very high; iii) When the load current naturally reaches 0, the arc is extinguished. However, at that moment, if the contacts are not parted enough, the voltage across the contacts will be higher than the dielectric strength of the (CB). An arc will appear again; and iv) The load current will continue flowing for half a cycle, often with reduced amplitude due to the arc resistance. This current restriction will cause energy dissipation within the (CB), potentially causing nozzle puncture

Re-ignition generally happens when the arcing durations are short in addition to the contacts of the (CB) are still not reached the complete clearance necessary to sustain the voltage stress [30]. To reduce the possibility of re-ignitions and, as a consequence, reduce the stress on the (CB), (SR), and associated equipment in a substation, it must be guaranteed that the contact gap of the (CB) has a withstand voltage capacity greater than the TRV at the instant the arc extinguishes [26]. Hence, the contact separation must be targeted at the re-ignition free window, as shown in Figure 6.

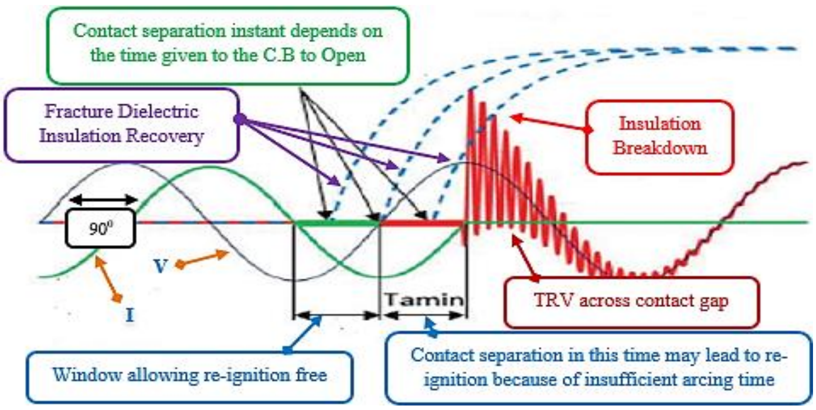

Figure 6. Controlled opening approach for operation without re-ignition [26]

When the natural current is almost zero, where the arc is supposed to be quenched, controlled switching will provide enough arcing duration and, as a result, there will be an adequate gap between the CB contacts. This will eliminate the eventuality of re-ignition by ensuring that the contact gap can withstand the expected (TRV). Furthermore, the arcing time is affected by the occurrence of (TRV) across the contacts.

3. DIELECTRIC RECOVERY CHARACTERISTIC

The dielectric properties between contacts differ from those for switching the current during short circuits when the circuit breaker is opened without a load or interrupted with a low current. The dielectric strength recovery property, also known as a cold recovery characteristic, is related to the intrinsic property of the (CB) and occurs during minor current switching. Table 1 shows the typical dielectric recovery characteristic of an SF6 interrupter. As can be observed, the dielectric strength first rises linearly as the contact distance widens before levels off [31].

Table 1 expresses the dielectric recovery voltage capability of the (CB). This work models the dielectric recovery curve as a line with a 400 kV/ms slope that remains constant after it reaches the standard switching withstanding threshold (1050 kV). If there is a voltage race across the contacts of a (CB), the arc will reignite if the internal dielectric recovery voltage of the circuit breaker is lower than the system recovery voltage. Otherwise, the arc will be extinguished.

Table 1. Typical dielectric recovery characteristic of an SF6 puffer interrupter

No.	Time (ms)	Voltage (KV)
1	0.5	200
2	1	400
3	1.7	600
4	2.25	800
5	2.8	1000
6	4.3	1200
7	7	1400

4. METHOD AND PROPOSED MODEL

This paper deals with a comprehensive model of the bank of (SR) within a 400 KV high-voltage system with a rated capacity of 150 MVAr, it also includes (CB) in addition to high-voltage equipment, using the way of connected windings and direct grounding. Table 2 presents the technical information about the reactor. A winding inductance, L and a resistance were connected in series, copper losses for each reactor phase are represented by RCu. With the single-phase equivalent model shown in Figure 7, simulations might be conducted as a consequence [26].

In previous works, researchers used many techniques and conventional countermeasures to reduce the switching transients, including damping reactors, pre-insertion resistors, or surge arresters. The method of "controlled switching" is reducing dangerous transients through the use of time-controlled switching operations. Commands to close or open the circuit breaker are delayed so that switching happen at the ideal instant of time in relation to the voltage phase angle. According to previous researches, the controlled switching method is able to prevent the occurrence of re-ignition. However, the (TRV) between the (CB) terminals remains high and nearly to the acceptable level. Consequently, any changes to the characteristics of the system, such as the stray capacitance of the reactor, could possibly lead to a re-ignition of the (CB).

In this regard, the proposed model represented by a circuit modification is needed to avoid any type of transient overvoltage due to the switching of the (SR) and to reduce the high magnitude of the (TRV) to prevent the occurrence of re-ignition. In part of the work, the circuit seen in Figure 7 was modified by including (CB_2) in series with a resistance across the (SR), as illustrated by Figure 8. The modification to the circuit would enable it to absorb the transient overvoltages generated through (CB_1) as well as the (SR). Thus, this modification was considered as overvoltage suppression.

Table 2. Parameters of the reactor

Parameter	Value	Unit
Equivalent source resistance (R_S)	0.77	Ω/phase
Equivalent source impedance (X_L)	6.19	Ω /phase
Stray capacitance on the source side (C_S)	4	nF/phase
Bus Inductance (L_B)	32	μH/phase
Stray capacitance on the load side (C_L)	3.2	nF/phase
corresponding reactor resistance (R_L)	1.2	Ω /phase
Inductance of reactor (L)	3.395	H/phase

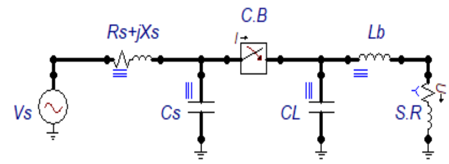

Figure 7. ATP-Draw equivalent model of a shunt reactor [26]

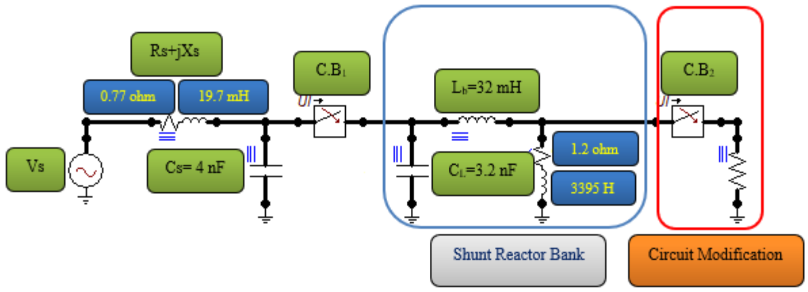

Figure 8. Circuit diagram for switching the reactor bank after modification

The procedure of this method was to close (CB_2) at the same time as when (CB_1) was open. This method ensured the suppression of overvoltages through the shunt reactor, while the TRV, through (CB_1), maintained the insulation from breaking down and prevented the occurrence of re-ignition. The work was implemented in two cases: firstly, using uncontrolled switching, and secondly, using controlled switching. To show the significance of the proposed method, both cases were achieved with and without a circuit modification.

5. RESULTS AND DISCUSSION

The circuit in this section was previously designed using the ATP-Draw software program. Therefore, to have a comprehensive understanding of de-energization, and to recognize the worst case and the ideal case during the interruption of a small inductive current with its related transient overvoltages, this work was divided into two parts, namely, uncontrolled switching, and controlled switching. To illustrate the differences between the two cases and to demonstrate the significance of the proposed method as indicated by the circuit modification and, on the other hand, its major impact in reducing transient overvoltages, both cases have included results of the simulations before and after the circuit modification.

5.1. Uncontrolled switching

The effects of uncontrolled switching will be discussed in this section of the paper, in addition to any negative values that may have an influence on the system's equipment. The voltage traces after the interruption for the (CB) and the (SR), when the (CB) opened at the moment of the maximum current value was attained. The results sufficiently showed that, within this unfavorable selection of opening time, both the (SR) and also (CB) generated overvoltages in each of their phases. The case of the current at a steady state is shown in Figure 9. While a typical example of current chopping has been given, shown in the Figure 10.

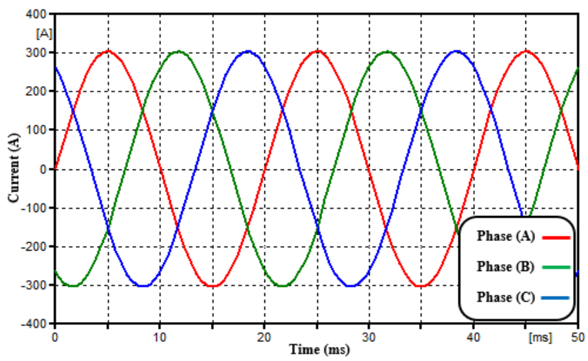

Figure 9. Case of current at steady state

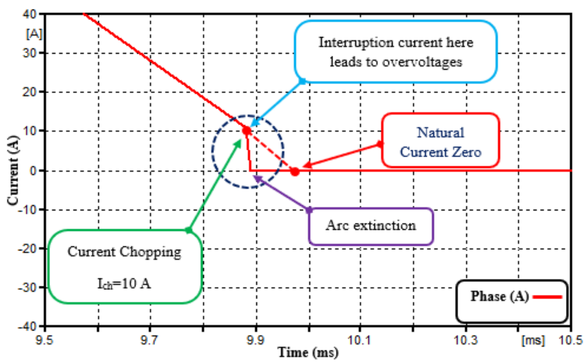

Figure 10. Current via C.B when I_{ch}=10 A

The medium employed for arc extinguishing will rapidly raise the remaining column resistance of a low inductive current, causing a sudden disconnection of the current before its natural zero crossing occurs. The electromagnetic transients that result in the switching of overvoltages are brought on by releasing of energy from the inductance of the reactor. The moment when the current is suddenly cut off, that is, the interruption occurs before reaching the natural zero point, has been shown. In this case, the voltage is almost at its maximum value, due to the nature of the inductive circuit. When a current chopping occurs, a very high value of stored energy resides in (SR). When the electromagnetic energy of the inductor is converted into electrostatic energy, electrostatic energy will be generated in the capacitor. As seen in Figures 11 and 12, respectively, it has previously been discussed how overvoltages caused by (CBs) and (SRs) might be a significant factor in the destruction of system components. This occurrence is known as the "inductive current chopping phenomenon," and depending on the amount of current is chopped, the inductive load will release its stored energy in another word significant overvoltages will result and it can be determined by monitoring the reactor circuit's energy balance, often referred to as chopping overvoltage.

Thus, the results will demonstrate the significance of the circuit modification as a proposed method and its important function in minimizing the transient overvoltages through the (CB) and (SR), consequently maintaining the equipment of the system. Figures 13 and 14 show the results of the proposed method represented by circuit modification on the (SR) and the (CB), respectively. Taking into account that despite the situation of an unfavorable selection of opening time, the results sufficiently demonstrate that the circuit modification decreased the overvoltages on the (SR) and (CB).

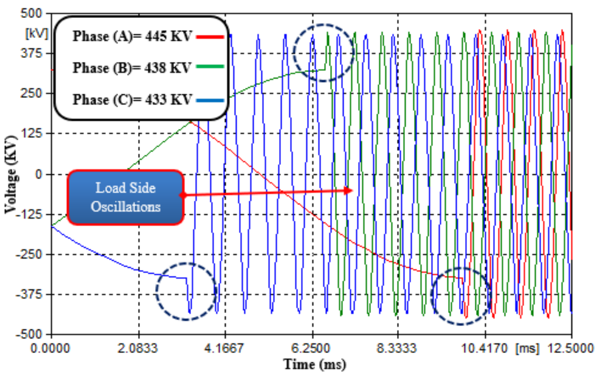

Figure 11. Voltage via shunt reactor when I_{ch} = 10 A

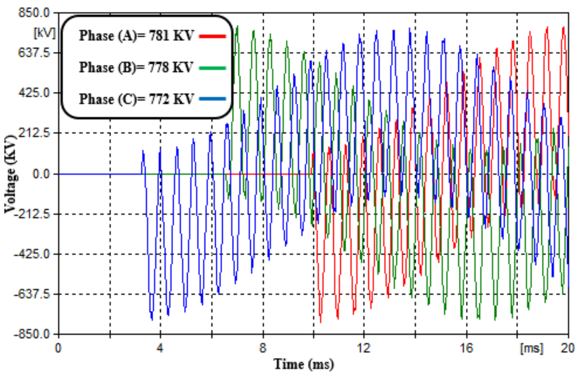

Figure 12. TRV across C.B when I_{ch} = 10 A

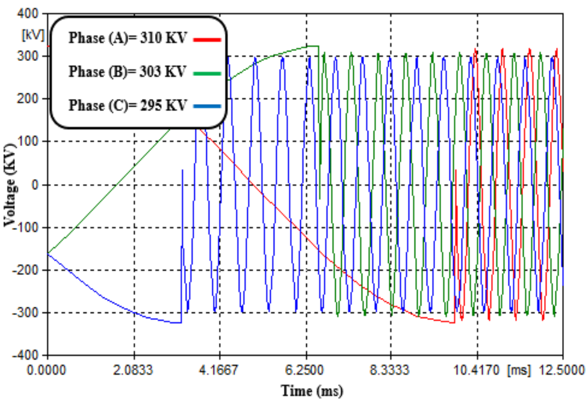

Figure 13. Voltage across reactor when I_{ch} = 10 A after circuit modification

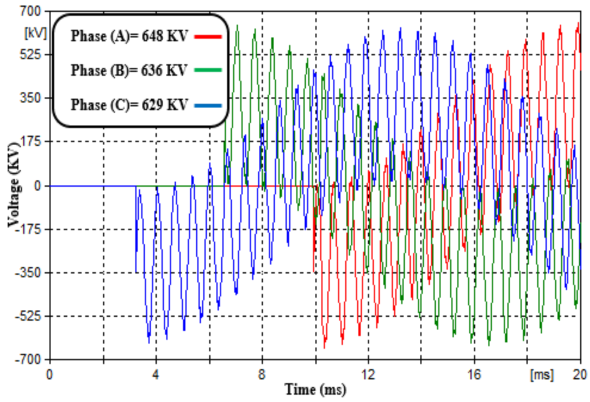

Figure 14. TRV across circuit breaker when I_{ch} = 10 A after circuit modification

This section presents the simulations to explain the variations in the overvoltage and TRV due to the design and configuration of the reactor. Additionally, because the ATP-Draw uses electrical modelling, the CB disconnecting chamber design and arcing duration had no impact on the simulations. If the peak value of the switching overvoltage surpasses the rated switching impulse withstand voltage of the equipment during an uncontrolled de-energization, the equipment may be in jeopardy. In this case, typical reignitions may take place, generating significant overvoltages on the shunt reactor. When assessing the efficiency of the insulation of the equipment, factors influencing, such as the age and number of switching operations must be taken into account. Therefore, the use of controlled switching with a circuit modification is needed.

5.2. Controlled switching

Various strategies have been proposed to prevent (CBs) from reigniting. One of the most recent ways to be used is switching employing point-on-wave (POW), commonly known as controlled switching, and it is relevant to the switching of (SRs). Controlled switching minimizes the mechanical and dielectric stress on the (CB) and decreases the probability of the occurrence of a restrike. In order to evaluate and estimate the effects on the magnitude of the overvoltage, as well as to give a more comprehensive understanding for the second case, where the simulation was implemented to represent the de-energization of (SR) by controlling the opening times of the (CB) poles and choosing the appropriate moment. The switch is basically in the closed position before executing the process for the purpose of representing the closed state. Then the command was given after specifying the appropriate time to open the poles of (CB). Figure 15 illustrate the moment of implementation of controlled switching which means at this moment (I_{ch} = 0 A), while Figures 16 and 17 show the voltage oscillograms through the (CB) and (SR), respectively after the moment of the interruption, which included the use of the controlled switching. The ATP-Draw software has the ability to control the opening time of the circuit breaker and determine the value of the current chopping. The circuit breaker is modelled using a time-controlled switch with a chopping magnitude of 25 A for each pole. Hence, by setting the switch's Imar parameter to 25 A, which is the required chopping level, the current chopping simulation in ATP-Draw is performed. The Imar parameter establishes what level of current the switch will interrupt.

To prevent reignitions that might result in failure of the (CB), the timing of the (CB) contact was controlled. The breaker was controlled to separate its contacts immediately following current zero. The circuit breaker contacts remained open, drawing up an electric arc that would be extinguished at the next current zero in less than half a cycle. The contacts were sufficiently separated when the arc was extinguished, thereby providing the highest dielectric strength. As a result, the (CB) was able to withstand the recovery voltage and avoid the occurrence of a reignition or restrike. Due to the absence of reignition in the 400 kV substation, phase-controlled for the CB demonstrates good performance in decreasing the overvoltage. The timing of the opening orders to the circuit breaker is delayed to ensure that switching or contact separation will take place at the ideal phase angle-related time instant. This is now the favored option for high-voltage and extra-high voltage shunt reactors for financial reasons. The efficiency of switching can be increased by continuously monitoring the line voltages and currents on each end of the breaker poles and by using modern power electronics. These overvoltages' and TRV's' potential magnitudes can be quite high. This, as a result, can place the reactor's insulation in jeopardy and accelerate the circuit breaker's ageing operation. To reduce switching transients, avoid equipment failures, and enhance power quality, controlled switching technology for opening and/or closing each separate circuit breaker pole, is a successful method for decreasing switching transients. In order to mitigate switching surges, controlled switching is currently a cost-effective alternative to a closing resistor.

The results below showed that suppressing overvoltages can be achieved within two significant points: first, the selection of the best time to open the (CB), and second, the main role importance of the circuit modification as a proposed method for the purpose of overvoltage suppression. As can be shown in Figures 18 and 19, it might be considered as an effective method for protecting the equipment of the system.

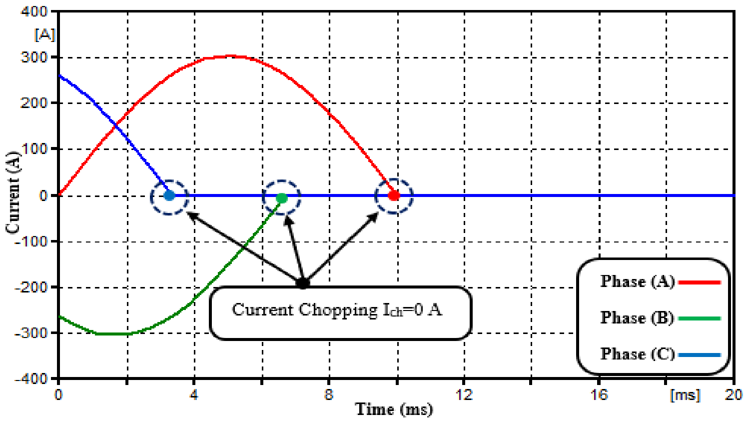

Figure 15. Current through C.B when I_{ch} = 0

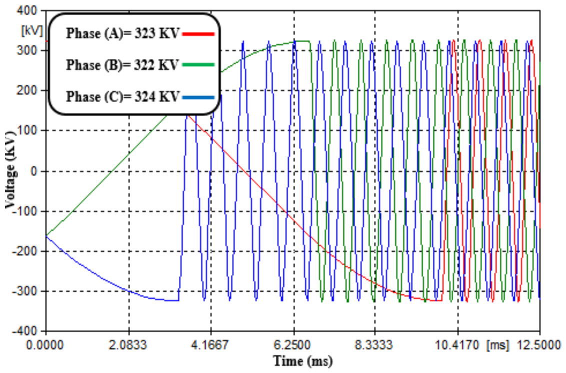

Figure 16. Voltage across reactor when I_{ch} = 0 A

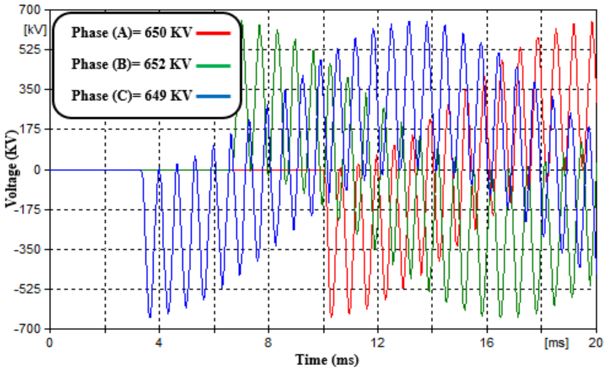

Figure 17. TRV value across C.B when I_{ch} = 0 A

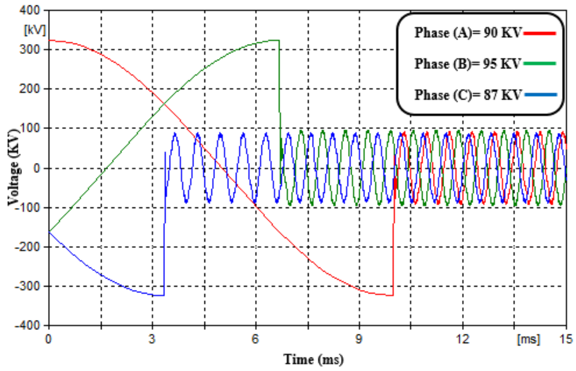

Figure 18. Voltage value across reactor when I_{ch} = 0 A after circuit modification

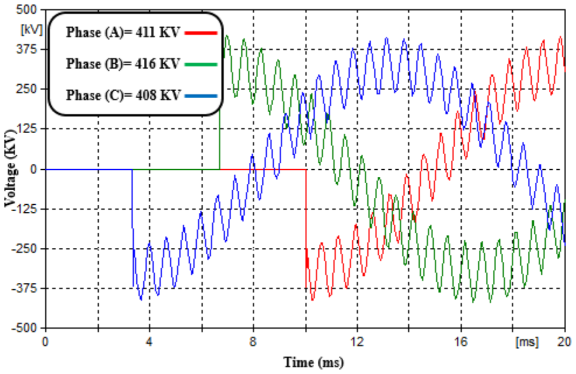

Figure 19. TRV value across C.B when I_{ch} = 0 A after circuit modification

The timing of the (CB) contact was controlled to prevent reignitions, which could result in breaker failures, according to the waveforms obtained by the transient overvoltage monitoring system. The (CB) was controlled to separate its connections immediately following current zero. Because of this, the (CB) was able to withstand the recovery voltage and avoid the occurrence of a reignition or restrike. Besides the use of controlled switching, the significance of the proposed method of circuit modification was the suppression of overvoltages arising from the (SR) and (CB). Figures 20 and 21 show the amplitudes of overvoltages on the (SR) and (TRV) between the uncontrolled phases and controlled phase with the circuit modification. It is obvious that the suggested method, which is represented by the circuit modification, was able to limit the maximum value of overvoltages produced on by current chopping to a very low level, and this would certainly prevent damage to the insulation.

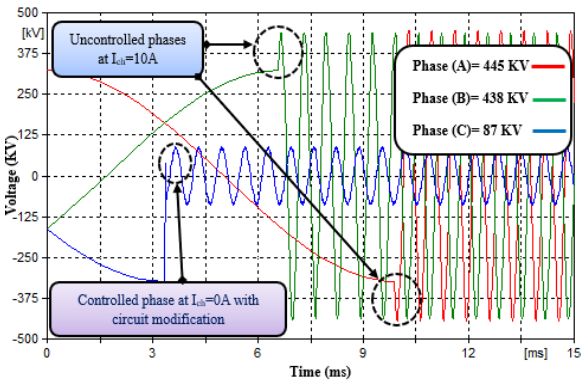

Figure 20. Overvoltages in shunt reactor during uncontrolled phases (for A & B) and controlled phase with the circuit modification (for C)

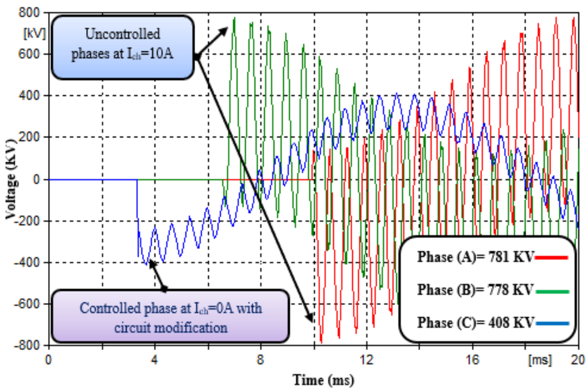

Figure 21. TRV during uncontrolled phases (for A & B) and controlled phase with the circuit modification (for C)

The magnitudes of the overvoltages across (SR) and (CB) for various chopping current levels are shown in Tables 3(a) and 3(b), which were recorded before to and after circuit modification. The results indicate that higher overvoltages were produced in case of the absence of circuit modification. Therefore, it is highly recommended to install a circuit modification on the (SR) terminals. Through the results obtained, the proposed method proved successful in suppressing high excess voltages even with high values of the current chopping, as the proposed modification of the circuit works to absorb most of the excessive voltages and discharge them through the CB_2, and thus this method ensures the preservation of switching equipment and protection of insulators from excessive voltages excessive.

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

	Overvoltages and (TRV) before circuit modification (150 MVAr)											
I_{ch}	Overvoltage value across (SR)						TRV value across CB					
	kV			p.u			kV			p.u		
	A	B	C	A	B	C	A	B	C	A	B	C
25 A	838	857	848	2.57	2.62	2.6	1190	1200	1196	3.65	3.68	3.66
20 A	698	688	707	2.14	2.11	2.16	1037	1030	1044	3.18	3.15	3.2
15 A	562	554	546	1.72	1.69	1.67	901	896	891	2.76	2.74	2.73
12 A	490	484	476	1.5	1.48	1.46	832	823	816	2.55	2.52	2.5
10 A	445	438	433	1.36	1.34	1.32	781	778	772	2.39	2.38	2.36
7 A	372	382	376	1.14	1.17	1.15	696	705	700	2.13	2.16	2.14
5 A	346	353	351	1.06	1.08	1.07	676	682	679	2.07	2.09	2.08
3 A	328	333	330	1	1.02	1.01	659	660	657	2.02	2.02	2.01
0 A	323	322	324	1	1	1	650	652	649	2	2	2

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

	Overvoltages and TRV after circuit modification (150 MVAr)											
I_{ch}	Overvoltage value across (SR)						TRV value across CB					
	kV			p. u			kV			p. u		
	A	B	C	A	B	C	A	B	C	A	B	C
25 A	765	780	778	2.34	2.39	2.38	1118	1136	1126	3.42	3.48	3.45
20 A	615	608	626	1.88	1.86	1.92	961	948	969	2.94	2.9	2.97
15 A	462	454	443	1.41	1.39	1.35	805	797	788	2.46	2.44	2.41
12 A	370	363	355	1.13	1.11	1.08	710	702	695	2.17	2.15	2.13
10 A	310	303	295	0.95	0.92	0.9	648	636	629	1.98	1.95	1.92
7 A	205	215	208	0.62	0.65	0.63	538	546	543	1.65	1.67	1.66
5 A	145	159	152	0.44	0.48	0.46	472	486	478	1.44	1.49	1.46
3 A	102	110	107	0.31	0.33	0.32	428	436	432	1.31	1.33	1.32
0 A	90	95	87	0.27	0.29	0.26	411	416	408	1.26	1.27	1.25

The highest switching overvoltage produced by current chopping across (CB) contacts should not be more than 3.6 p.u. or 80% of the peak value of the switching impulse withstand voltage [18], [27]. The overvoltage factor was kept to acceptable value in each case. The overvoltage factors in the improved circuit were significantly lower. The (SR) switching-related overvoltage's were significantly decreased by the circuit modification.

The effect of the current chopping on the (CB) has been tested by selecting different values of the current chopping starting from the lowest value of (0) A to a high value of 25 A. The process of (SR) disconnected was done using the simulation software ATP-Draw program, through which the process of controlling the opening time of each pole of (CB). This process was completed and overvoltage values were recorded for each current chopping value. Figures 22 and 23 show the simulation results. According to these figures, the magnitude of the overvoltage in the (SR) and the (CB) rose with the amplitude of the chopped current.

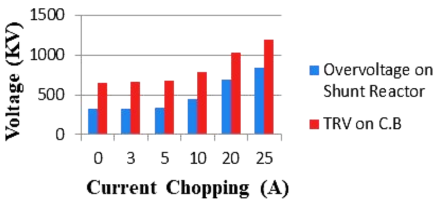

Figure 22. Magnitude of overvoltage before circuit modification

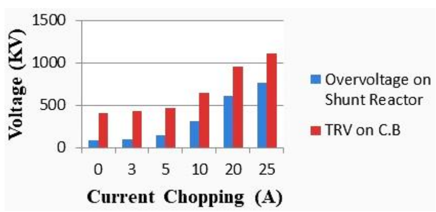

Figure 23. Magnitude of overvoltage after circuit modification

The overvoltage level was always below 2.5 p.u. within the realistic current chopping range of the circuit breaker. For chopping currents above 20 A, there was a more significant rise in the magnitude of the overvoltage. Nevertheless, it is unlikely that these numbers will appear in real modem (CB). With a significantly larger overvoltage, the overvoltage across the (CB) increased similarly to the (SR). The results from this study, which were obtained using the proposed method, have been compared with those from prior studies, where it was found that the voltage of the (SR) decreased by 2.58% in [13], and the percentage of reduction in the voltage was 13.5% in [32], while the ratio was 18.3% in [33]. Regarding of this work, the overvoltage was significantly decreased and a magnificent rate of 89% was obtained.

6. CONCLUSION

This study discussed cases of overvoltage resulting from the switching transients process, and it was done according to two types of the switching process, the first is the uncontrolled switching, while the second is the controlled switching, in which the voltage were tested for different levels of the current chopping of a 400-kV (SR) system. The investigation of overvoltage suppression techniques was addressed by the simulations in this paper. The transient phenomenon produced by switching of (SR) using ATP-Draw software program has been explained. Current chopping results in a sharp increase in the (TRV) across the (CB) and an overvoltage during the de-energization case across the (SR). It can cause the arc to reappear after being disconnected at natural current zero. This case is known as re -ignition and to reduce its danger and the resulting high stress on both (CB) and (SR) and the connected equipment in addition to the insulation and sub -stations, It must be guaranteed that at the moment of arc extinction that the (TRV) is less than the insulation contacts capability. In this study, different current chopping values were examined for both uncontrolled and controlled de-energization before and after the circuit modification, and the effective use of the proposed method demonstrated the reduction of overvoltages, where the overvoltages in this work dropped significantly and achieved a great rate of 89%.

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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 engineering/electrical department/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 snice 2006. He can be contacted at email: mazyed.altak@uomosul.edu.iq.

Mohd Fadzil bin 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 obtained his Bachelor of Science (BSc) in Electrical Engineering in 2001 from the Electrical Engineering Department, College of Engineering, University of Mosul, Iraq. Then he was appointed as an assistant engineer in the same mentioned department. After that, he got MSc 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 Electrical Engineering Department, 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 Electrical Engineering Department, College of Engineering, University of Mosul. 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.