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Assessment and Mitigation Studies of Voltage Sags during Sympathetic Inrush Current

Nurul Fatin Nadhirah Subli[1], Hana Abdull Halim[1,2,*], Haziah Abdul Hamid[1,2]

[1] Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis, Perlis, Malaysia
[2] Centre of Excellence for Renewable Energy, Universiti Malaysia Perlis, Perlis, Malaysia

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ABSTRACT

The system voltage may be negatively impacted by the transformer's energisation which draws a large value of magnetising inrush current for a few seconds. During the transformer's energisation process, it experiences an unexpected saturation. When the transformer is saturated, the growth of magnetising inrush current, sympathetic inrush current and voltage sags are a few issues that are appear. Numerous variables that affect the inrush current and the resulting voltage sags were taken into consideration. This is due to the fact that the energisation of a large power transformer may result in a high voltage sag which relies on a value of parameters, including the duration of the circuit breaker closing time. One of the most essential objectives for power quality is the research of voltage sags that appear in a network. The goal of this project is to investigate sympathetic and inrush currents as well as to assess the voltage sag that occurs during transformer energisation and how severe it is. In this paper, the voltage sags are analysed by modelling 100kVA, 11kV/415V of wye-delta of single line (circles) transformer and using PSCAD software. It is expected to observe the magnitude, the duration and the percentage of voltage sags in order to make a comparison result between single connected transformer, two parallel-connected transformers and three parallel-connected transformers. To predict the severity of the sympathetic inrush current, the effects of voltage sags and their assessment is developed. As a result, it has been shown that the more energisation of the transformers, the peak of inrush current increases causing the higher magnitude and the longer duration of voltage sags. In conclusion, the voltage sags also become severe and persists for a longer duration when the number of transformers in operation are increased.

1. Introduction
1.1 Background Study

Transformers is a very essential components of power grids and the energisation of the transformers is a routine process in a distribution network where are taken by Mo *et al.,* and Moradi *et al.,* [1,2]. According to author Athire *et al.,* [3], due to the rapid advancement of technology on every single day, the load demand has significantly increased. All the problems that are occurs that

* *Corresponding author.*
E-mail address: hanahalim@unimap.edu.my

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caused by the transformer energisation are nothing new as presented by Emin *et al.,* [4]. Over the past decade, the difficulty of detecting the transformer transients particularly is inrush current. An energisation of the transformer is frequently related with the inrush current phenomena. A transformer generates a magnetising inrush current that serves as the start-up current when it is turned on for the first time and having a high value of current in a short period. Not only the single connected transformer but the parallel-connected transformers also were significantly impacted by the energisation of the transformer.

An early researcher such as Moradi *et al.,* [2], Purohit *et al.*, [5] and Liu *et al.,* [6] presented that the transformer's energisation can draw a higher value of inrush current that can produces a variety major of power system concerns including harmonic resonance and overvoltage, protection relay mal-operate and also voltage sags. Besides, it also gives the negative effects on the transformer, which can shorten its lifespan, diminishes the power quality and in a severe condition, result in deterioration of transformer insulation that observed by Emin *et al.,* [4], Peng *et al.,* [7], Bardanov *et al.,* [8]. According to the Bardanov *et al.,* [8], Solak *et al.,* [9] and Vinnal *et al.,* [10], voltage sags is one of the most noticeable concerns with power quality for a longer period and since the load has changed, all the issues that are relating with the power quality must be taken into consideration that observed in Athire *et al.,* [3]. As presented in Sahoo *et al.,* [11], power quality is defined as the ability of the system to provide a safe and reliable power supply. In this project, a greater concern has been given to the growth of inrush current that can lead a negatively impacts to the voltage sags. Given the increasing load demand and rapid technological advancements, the research gap centers on the need for improved methods to mitigate inrush currents on power systems, specifically in the context of voltage sags. The contribution of study primarily focuses on addressing this research gap by developing strategies to minimize voltage sag's occurrences and enhance overall power quality.

1.1 Inrush Current Phenomena

Inrush current phenomena are classified into two which is magnetising and sympathetic inrush current phenomena. According to an early author Heretík *et al.,* [12], Kumbhar *et al.,* [13], Tao *et al.,* [14] and Cao et al., [15], the magnetising inrush current is created by energising a single transformer which no additional transformers that are attached to the power system network. The other characteristics is when a no-load transformers are energised as mentioned earlier in Mo *et al.,* [1], Dejun *et al.,* [16], and Li *et al.,* [17]. As stated in Zai *et al.,* [18], Fan *et al.,* [19] and Smith *et al.,* [20] the magnetising inrush current can be up to the several times than the value of rated current and it can cause overcurrent. Due to this overcurrent, it has possibility to burning the transformer core and the other components. Besides, when a transformer is energised while having another transformer in operation, the sympathetic inrush current phenomena will develop as mentioned earlier in Tao *et al.,* [14], Abdull Halim *et al.,* [21], Sawarkar *et al.,* [22] and Yahiou *et al.,* [23]. These days, the sympathetic inrush current is growing more significant with the existence of the numerous of transformers. This is due to the fact that it not only energising two transformers, but it may be energising more than transformers at once. On top of that, the transformers may be energising or switching all at the same times that are taken from Nadhirah *et al.,* [24]. There are a few characteristics of magnetising and sympathetic inrush current in order to differentiate it. Table 1 shows the comparison between the magnetising and sympathetic inrush current that are taken from previous studies such as Purohit *et al.,* [5], Kumbhar *et al.,* [13] and Sawarkar *et al.,* [22].

Table 1
The characteristics to differ between magnetising and sympathetic inrush current

Magnetising inrush current	Sympathetic inrush current
When it is rise, it can reach to the peak level and have a large amplitude of current.	When it is rise, it does not reach to the peak level and rises gradually.
When it is decay, it gradually decays to zero.	When it is decay, it does not reach to the zero and persists for a long duration.
Can rise quickly in a short time.	Can rise but it takes a longer time.

1.2 Concept of Voltage Sags

Voltage sags is the worst one that caused by faults and it can extremely dangerous. An early researcher Peng *et al.,* [7], Blanco *et al.,* [25], Seo *et al.,* [26] and Zhong *et al.,* [27] present that the voltage sags or also known as voltage dips is a temporary reduction of the magnitude of rms voltage that brought by the higher value of inrush current which occur for between 10% to 90% of nominal voltage in 0.5 cycles until 1 minute as stated in Vinnal *et al.,* [10] and Node *et al.,* [28]. According to Hana *et al.,* [29], the characteristics of the voltage sags are classified into two main categories which is the magnitude and the duration. The magnitude of the voltage sags is determined by the reduction in voltage from a particular normal system and the duration of the voltage sags is measured from the beginning to the end of the voltage as shown in Figure 1.

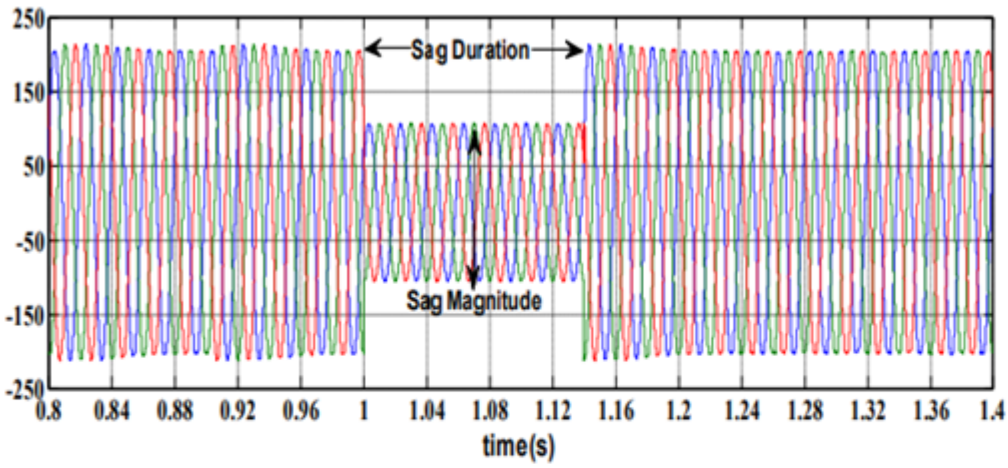

Fig. 1. The waveform of the magnitude and duration of voltage sags as presented in Surender K. Grewal *et al.,* [30]

From Figure 2, it also shows that the transients are defined as any phenomena that occurs with the duration under 0.5 cycles, whereas the interruptions are classified when the magnitudes are below than 10%. For the normal operating voltage, the range of the magnitude is between 90% to 110% and for the duration that longer than 1 minute is classified as undervoltage. In addition, if it happens between 0.5 cycles until 1 min and has a magnitude greater than 110%, it is referred as a swell. Nevertheless, if it lasts longer than 1min but has the same magnitude, it is called as an overvoltage. The voltage sags are classified into three types which is instantaneous, momentary and temporary. All these three voltage sags having a same magnitude but different in their duration.

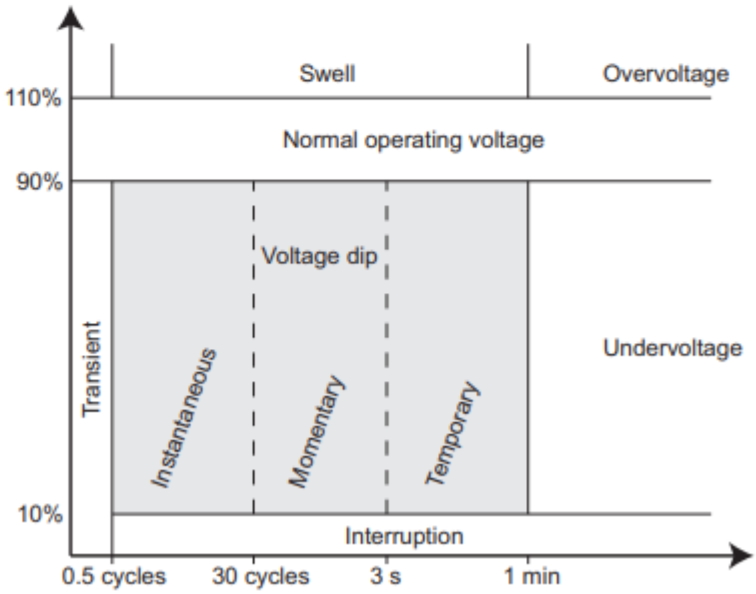

Fig. 2. The definition of voltage sags [28]

2. Methodology

2.1 The Simulation Modelling

By applying 100 kVA, 11 kV/415V wye-delta of single-line (circles) transformer, resistance, inductance and capacitance as provided in Table 2, the simulation of inrush current and voltage sags is explored. Ammeter, multi-meters and circuit breakers are the additional components that used in this schematic circuit. The inrush current is measured by ammeter while the multi-meter is used to measure the voltage sags. Other than that, there are indeed two primary types of circuit breaker which is electrical circuit breaker and mechanical circuit breaker. These two types differ in their operational mechanisms and characteristics. Electrical closing circuit breaker involves the use of electrical control signals to initiate the opening and closing of circuit breaker contacts while the mechanical closing of circuit breaker relies on physical mechanisms such as springs, solenoids or lever to open and close the circuit breaker contacts. Additionally, the circuit breaker is utilised to monitor the electrical power system, and when it is closed, current is flowing since all of the elements are connected to one another. Hence, this section demonstrates the schematic circuit as well as the simulation result of inrush current and voltage sags for single-connected transformer, two parallel-connected transformers, and three parallel-connected transformers. To compare the inrush current, the magnitude, and the duration of voltage sags, all three findings are analysed. All the schematic circuit are presented by using PSCAD software.

Table 2
Parameters of the transformer modelling

Parameters	Value
Transformers	100kVA, 11kV/415V
Resistance	100Ω
Inductance	0.5H
Capacitance	100F
Frequency	50Hz

2.2 Formula of Voltage Sags

The computation for voltage sags also provided for this sub-chapter. This calculation can determine an estimate value of voltage sags and how much it may exceed the nominal voltage.

$$Voltage\ sag\ (\%) = \frac{Normal\ voltage - Minimum\ voltage\ during\ sags}{Normal\ voltage}\ x\ 100\%$$

Normal voltage = Representing the typical voltage in the power system under normal operating conditions.
Minimum voltage during sags = The lowest voltage level reached during the sag.

$$RMS\ Voltage\ \ (V_{RMS}) = Nominal\ voltage\ x\ \sqrt{2}$$

$Magnitude\ of\ voltage\ sags\ (kV)$ The lowest voltage level reached during the sag.

$$Duration\ of\ voltage\ sags\ (T) = t_2 - t_1$$

$t_1 =$ the time where the voltage begins to drop.

$t_2 =$ the time where the voltage returns to the nominal voltage.

2.3 Single-Connected Transformer

As shown in Figure 3, which includes a single transformer (T1), one multi-meter (Vrms1), one ammeter (Ia), and one circuit breaker (BRK) is used to explore the inrush current and voltage sags. Besides, the time of operation breaker for the circuit breaker BRK is set to 0.5 s, indicating that in 0.5 s the circuit breaker will close and the transformer will begin to energise. The inrush current will appear when the transformer is powered on for the first time without being connected to any other loads. These occurrences are referred as magnetising inrush current.

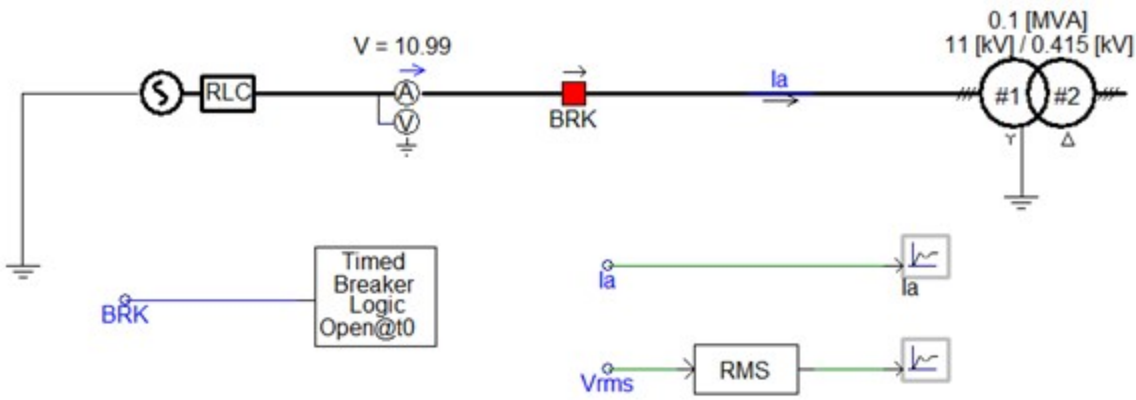

Fig. 3. Schematic circuit for single-connected transformer

2.4 Two Parallel-Connected Transformers

The sympathetic inrush current is produced by utilising two ammeters (Ia and Ib), two multi-meters (Vrms1 and Vrms2), two circuit breakers (BRK 1 and BRK 2) and all are connecting in parallel with the transformers namely as transformer (T1 and T2) that having a same rating as presented in Table 2. The circuit breaker is configured to close in the schematic circuit, and the breaker operation time is set to 0.5 s and 1.0 s. Figure 4 shows a schematic circuit for two parallel-connected transformers.

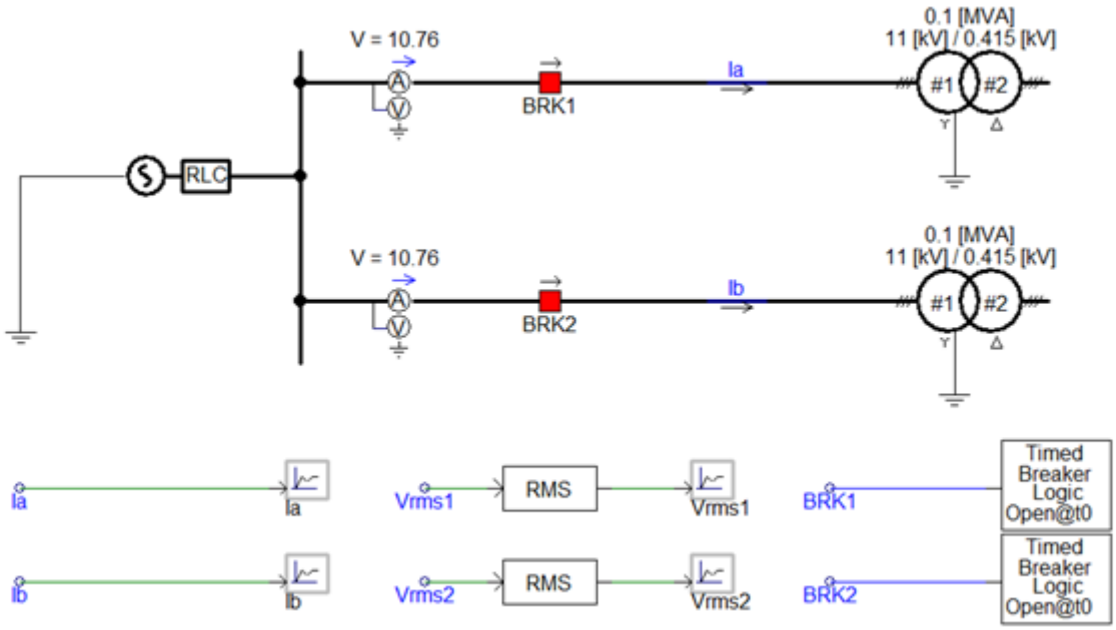

Fig. 4. Schematic circuit for two parallel-connected transformers

2.5 Three Parallel-Connected Transformers

In Figure 5, there are three multi-meters (Vrms1, Vrms2 and Vrms3), three ammeters (Ia, Ib and Ic), three circuit breakers (BRK1, BRK2 and BRK3), three transformers (T1, T2 and T3) are shown and all of the equipment that have the same rating. The operation time for BRK 1 is set to 0.5 s, BRK2 is 1.0 s while BRK 3 is 1.5 s, respectively.

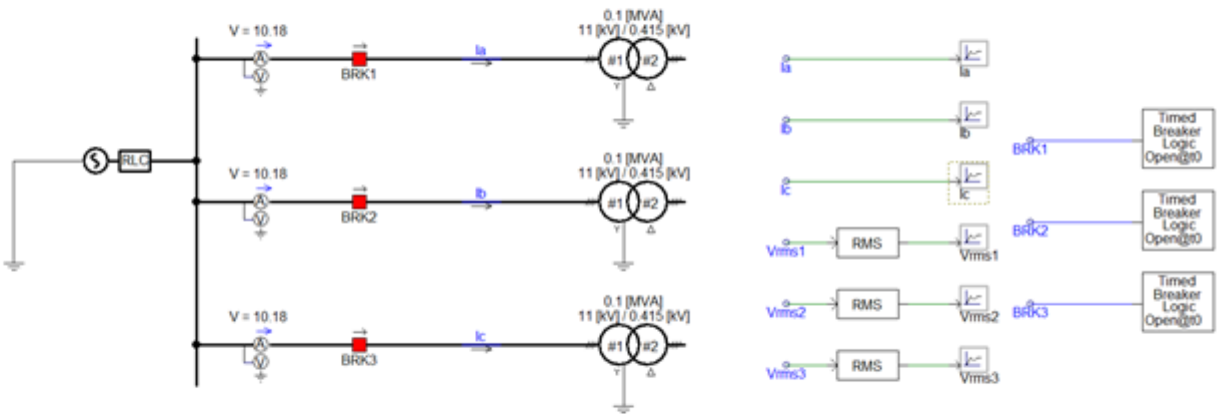

Fig. 5. Schematic circuit for three parallel-connected transformers

3. Results

3.1 Single-Connected Transformer

Figure 6 demonstrates that the inrush current reach to 0.01243 Ka as its peak after 0.5 s and gradually declines until 1.5 s have passed before it reaches 0 Ka.

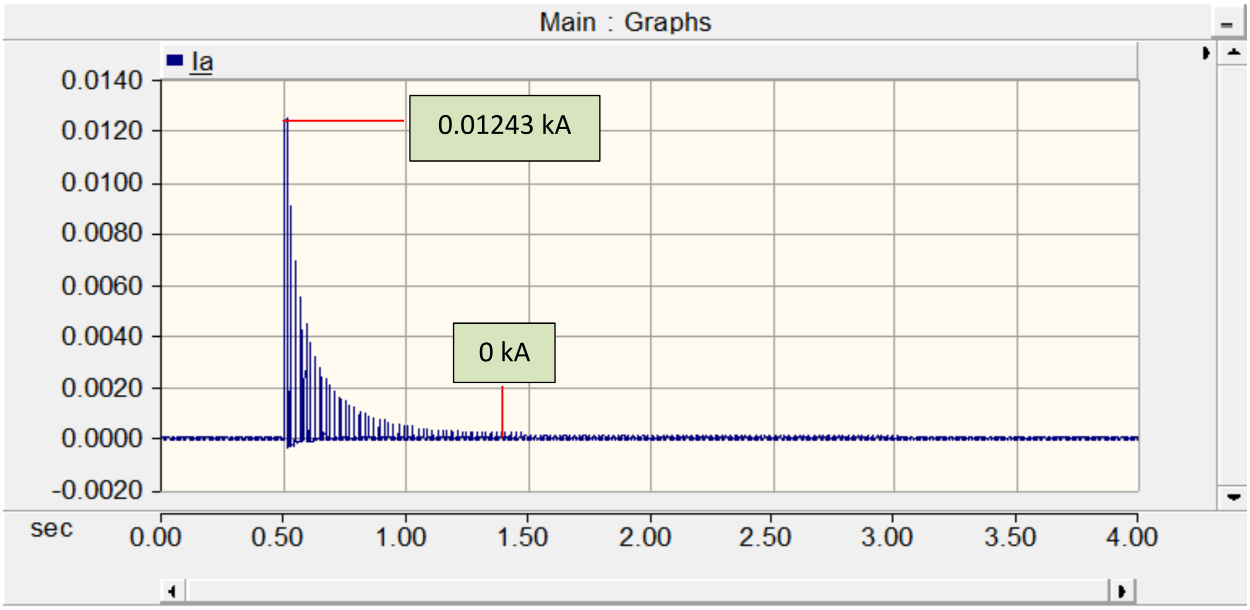

Fig. 6. Simulation result of single-connected transformer for inrush current

According to Figure 7, the voltage sags also are begun to develop as soon as the transformer turns on. This indicates that before 0.5 s, the voltage is kept at 11 Kv and afterwards, it starts to drop until it achieves 10.4858 Kv as its magnitude. The voltage sags occur at 0.8005 seconds for a duration between 0.5010 to 1.3015 s. With the voltage remaining at 10.9900 Kv, the voltage will reach steady-state in around 1.3015 s.

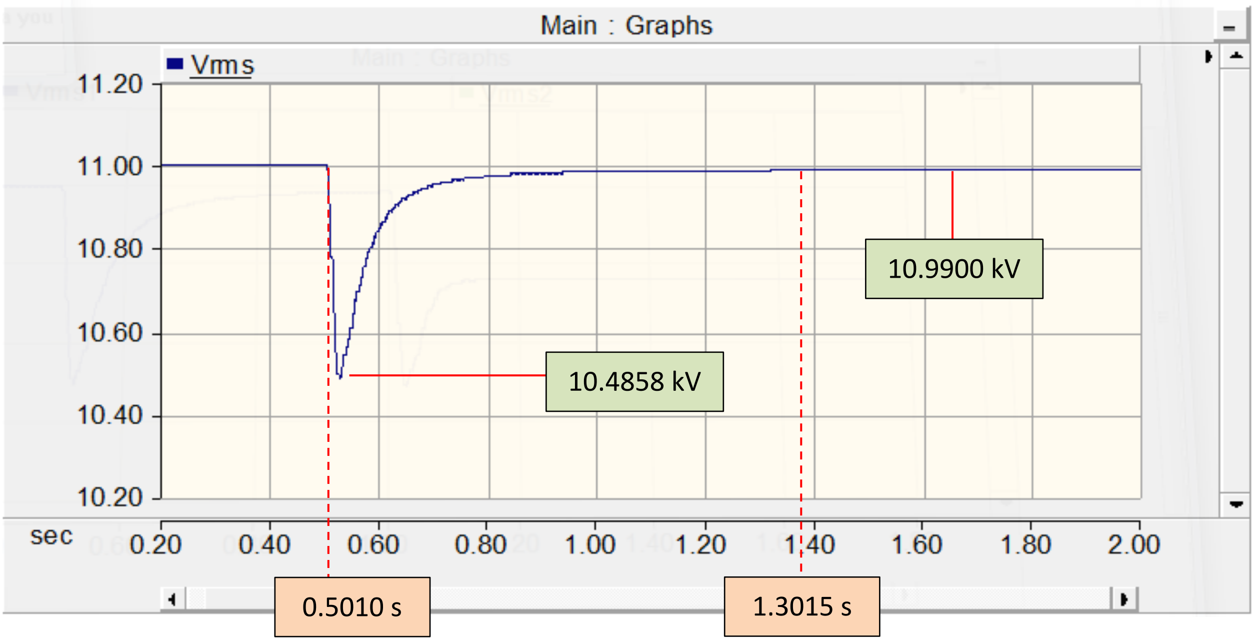

Fig. 7. Simulation result of single-connected transformer for voltage sags

3.2 Two Parallel-Connected Transformers

As seen in Figure 8 when T1 is switched on for the first time without the other transformers being in use, a magnetising inrush current develops. The magnetising inrush starts at 0.5 s and reaches 0.01246 Ka before continuing to decline at 1.0 s. After 1.0 s, the T2 is switched on and since the other transformer (T1) was already switched on, the whole system experienced a sympathetic inrush current. Getting back to the theory, when the T2 is turned on and by having the previous transformer (T1) which is already turned on, causes a sympathetic inrush current to arise. Since the sympathetic inrush current rises in a negative value, roughly about -0.00045 Ka, the inrush current approaches 0.01363 Ka for its maximum.

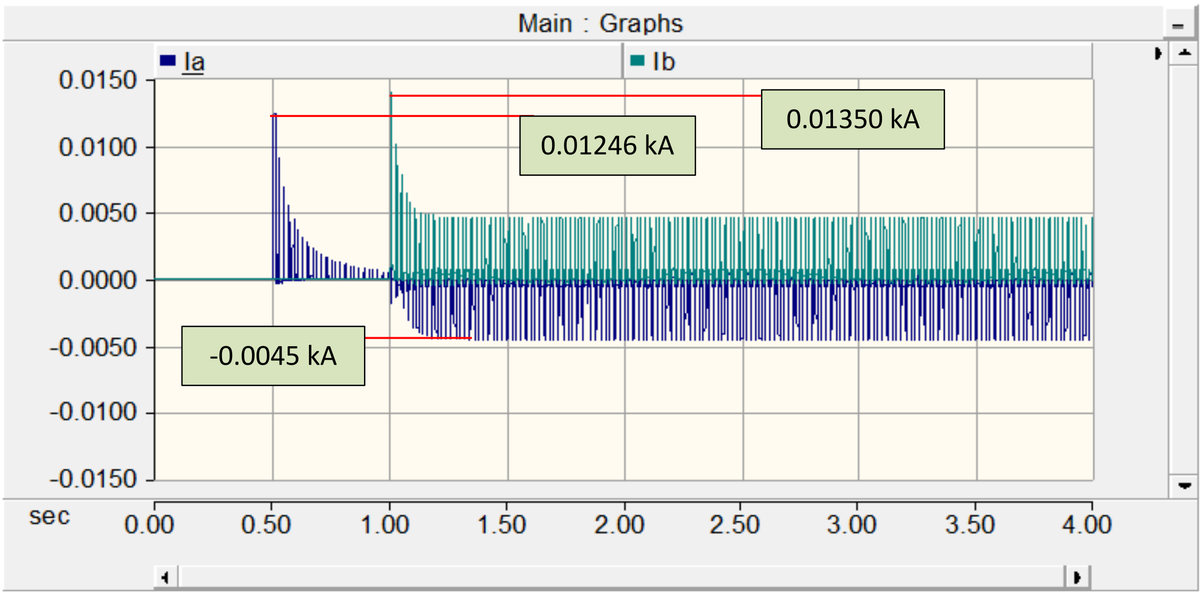

Fig. 8. Simulation result of two parallel-connected transformers for sympathetic inrush current

In order to analyse the voltage dips that occur during the energisation of the transformers, the operation time of circuit breaker are adjusted to different times such as 0.5 s and 1.0 s and Figure 4 displays that all the transformers are connected with the multi-meter. According to Figure 9, the voltage drops significantly from 11 Kv to 10.4910 Kv after 0.5 s and the voltage sags continue for 0.3580 s with the range between 0.5020 s until 0.9600 s. Then, the voltage rises till it reaches 10.9810 Kv and remains there for a several seconds before returning to the normal value. Following with the operation of circuit breaker in 1.0 s, the voltage began to decrease once more until the magnitude reaches 10.4820 Kv, meaning that the voltage sags in 1.0 s were greater than 0.5 s. Before becoming continuous at 10.7600 Kv, the duration of voltage sags is 0.1290 s which is within 1.0030 s to 1.1220 s. In addition, it can be seen in Figure 8 that the time it takes for the current to decay is also shorter, indicating that the duration of the voltage sags for 1.0 s is shorter than 0.5 s.

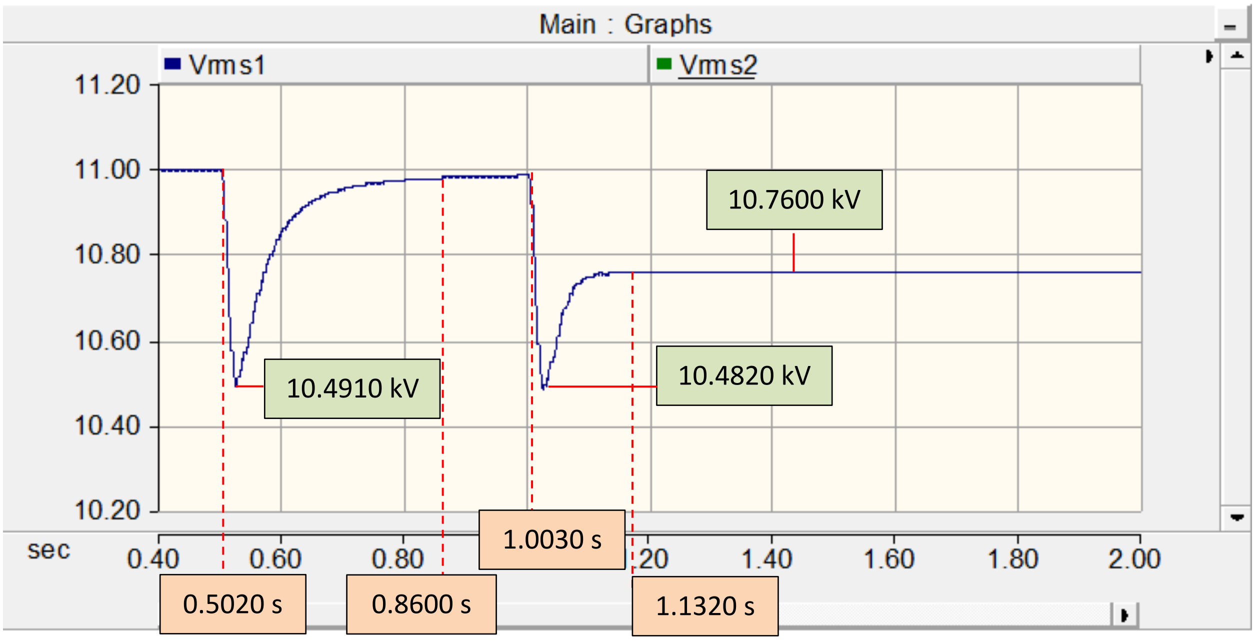

Fig. 9. Simulation result of two parallel-connected transformers for voltage sags

3.3 Three Parallel-Connected Transformers

According to Figure 10, the magnetising inrush current happens in T1 when the transformer started to energise in 0.5 s and reaches 0.01252 kA. However, it quickly degrades until dissipating after 1.0 s, which is when the BRK2 is closed. Aside from that, the sympathetic inrush current develops throughout the entire system but at a small value of -0.0045 kA, reaching a maximum of 0.01322 kA before progressively declining until 1.5 s. Since the T3 is energised while having two transformers that were previously in operation, the inrush current reaches its greatest peak in 0.01349 kA at 1.5 s. The energisation of three transformers causes the sympathetic inrush current to expand from -0.0045 kA to -0.0100 kA, where it becomes more severe. It should be noted that, the higher the number of transformers that are used, the sympathetic inrush current also higher. The sympathetic inrush current occurs for the overall system since the inrush current is decreasing but not reaching 0 kA.

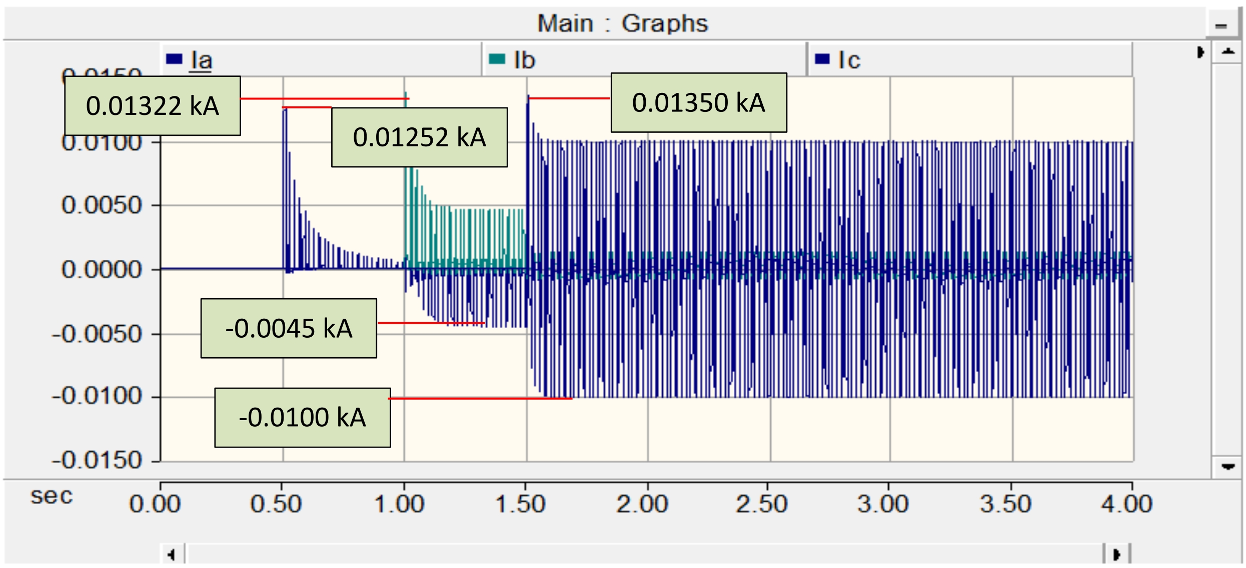

Fig. 10. Simulation result for three parallel-connected transformers for sympathetic inrush current

The different time operation of circuit breaker can give an effect to the voltage sags since the T1 is energised at 0.5 s, T2 at 1.0 s and T3 at 1.5 s. Therefore, the voltage sags are dropping three times in accordance with how the circuit breakers are working. As shown in Figure 11, when BRK1 begins to run at 0.5 s, the voltage is drop slightly for 0.3486 s starting from 0.5039 s till 0.8525 s. Before the voltage continues to rise till 10.9890 kV and remains there for a short while, voltage sags can reach a magnitude of 10.5155 kV. In contrast to the voltage reduction at 0.5 s, the voltage drops for the second times as soon as the BRK2 is switched-on at 1.0 s, peaking at 10.4712 kV. Only 0.1670 s pass between the reduction and the voltage remaining at 10.7512 kV. Last but not least, when transformer 3 is switched-on at 1.5 s, the reduction of voltage happens again until hit 10.1705 kV at its peak. Due to the larger sympathetic inrush current at 1.5 s, the magnitude of voltage sags is quite higher compare to 0.5 s and 1.0 s. Furthermore, the voltage are decreases for a short duration which is between 1.5010 s until 1.5775 s before raising once more to reach steady state at 10.1810 kV. It should be noted that although the magnitude of voltage drop is greater, it only lasts momentarily. As can be observed that the duration of the voltage sags when the transformer turns on without energising the other transformer is quite longer than by having the other transformers in operation. By comparing within energisation at 0.5 s and 1.5 s, the duration for the voltage sags happen is 0.3486 s for 0.5 s and 0.0765 s for 1.5 s. This is because the current is decay slowly in 0.5 s while the current is decay rapidly after 1.5 s as shown in Figure 10.

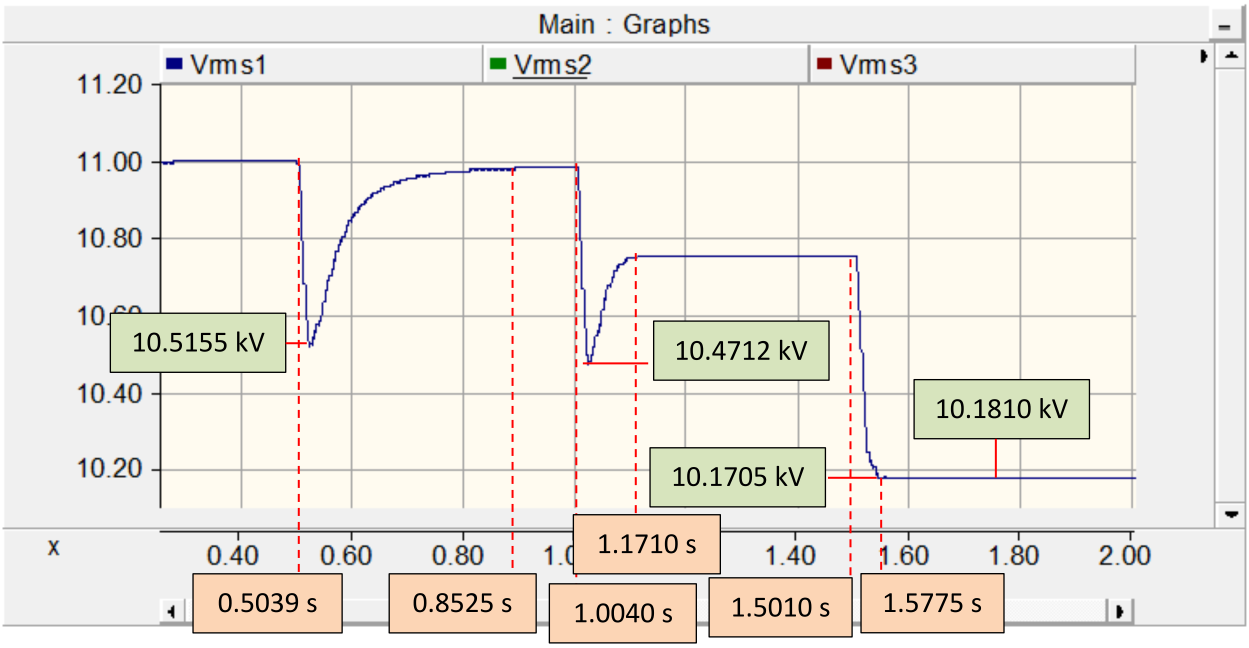

Fig. 11. Simulation result for three parallel-connected transformers for voltage sags

3.4 Result and Discussion

Table 3 displays the reading of inrush current, magnitude and duration of voltage sags for single, two and three-parallel connected transformers. In this research, there are dealing with three types of transformer connections such as single connected transformer, two and three transformers that are connected in parallel. Since there are dealing with three different types of transformer connections, there are having three different closing times that are allows to explore how these variations can give an impact to the magnitude and duration of voltage sags. The actual times for circuit breaker operation times can be vary to any acceptable values within the range of minimum and maximum that industry used. The key criterion is that selected operation times should be able to generate voltage sags with the desired magnitude and duration accurately, ensuring that can conduct without any error in order to make a comparison. For the single-connected transformer, there are only energised at 0.5 s, 0.5 s and 1.0 s for two-parallel connected transformers while 0.5 s, 1.0 s and 1.5 s for three-parallel connected transformers. By focusing on the magnitude of voltage sags, it presented that the voltage 10.4858 kV at 0.5 s for single connected transformer while 10.4820 kV at 1.0 s for two-parallel connected transformers and 10.1705 kV at 1.5 s for three-parallel connected transformers. Figure 12 illustrates the comparison of voltage reduction from the supplied voltage with varying transformer numbers. In addition, the duration for single transformer only happens in one duration whereas for three transformers are happens into three durations. In summary, voltage sags develop for longer periods of time for three transformers than for a single transformer. According to the results of this simulation, the peak of voltage sags also rises as the number of transformers in use increases.

For the inrush current, when the transformer is turned on for the first times, the current reach 0.01243 kA at its peak and the current slowly decay until 1.5 s whereas the current fallen to 0 kA. For two-parallel and three-parallel connected transformers, there have a same peak of inrush current which is 0.01350 kA, however the sympathetic inrush current values are differ. As opposed to two transformers, which have a sympathetic inrush current of -0.0045 kA, three transformers have a sympathetic inrush current of -0.0100 kA. As indicated in Table 3, it can see how the peak of sympathetic inrush current can be impacted by the number of transformers operating while Table 4 displays the reading of the magnitude of voltage sags in RMS value. It has been noticed that the more energisation of the transformer, the peak of sympathetic inrush current that appears also increases. Additionally, pursuant to the concept that when the sympathetic inrush occurs in the system, the magnitude of the voltage sags become higher. The higher value of the voltage sags might result in a low voltage supply to the current, which makes the load must work harder.

Table 3
Energisation of single, two and three-parallel connected transformers

Transformer	Magnitude of voltage sags (kV)			Duration of voltage sags (s)			Inrush current and sympathetic inrush current (kA)		
	Energi-sed at 0.5 s	Energi-sed at 1.0 s	Energi-sed at 1.5 s	Energi-sed at 0.5 s	Energi-sed at 1.0 s	Energi-sed at 1.5 s	Energi-sed at 0.5 s	Energi-sed at 1.0 s	Energi-sed at 1.5 s
Single-connected transformer	10.4858	-	-	0.8005	-	-	0.01243	-	-
Two-parallel connected transformers	10.4910	10.4820	-	0.3580	0.1290	-	0.01246	0.01350 and -0.0045	-
Three-parallel connected transformers	10.5155	10.4715	10.1705	0.3486	0.1670	0.0765	0.01252	0.01322 and -0.0045	0.01350 and -0.0100

Table 4
The magnitude of voltage sags in RMS value

Transformer	Magnitude of voltage sags (kV)			RMS value (kV)		
	Energised at 0.5 s	Energised at 1.0 s	Energised at 1.5 s	Energised at 0.5 s	Energised at 1.0 s	Energised at 1.5 s
Single-connected transformer	10.4858	-	-	14.8291	-	-
Two-parallel connected transformers	10.4910	10.4820	-	14.8365	14.8238	-
Three-parallel connected transformers	10.5155	10.4715	10.1705	14.8712	14.8089	14.3833

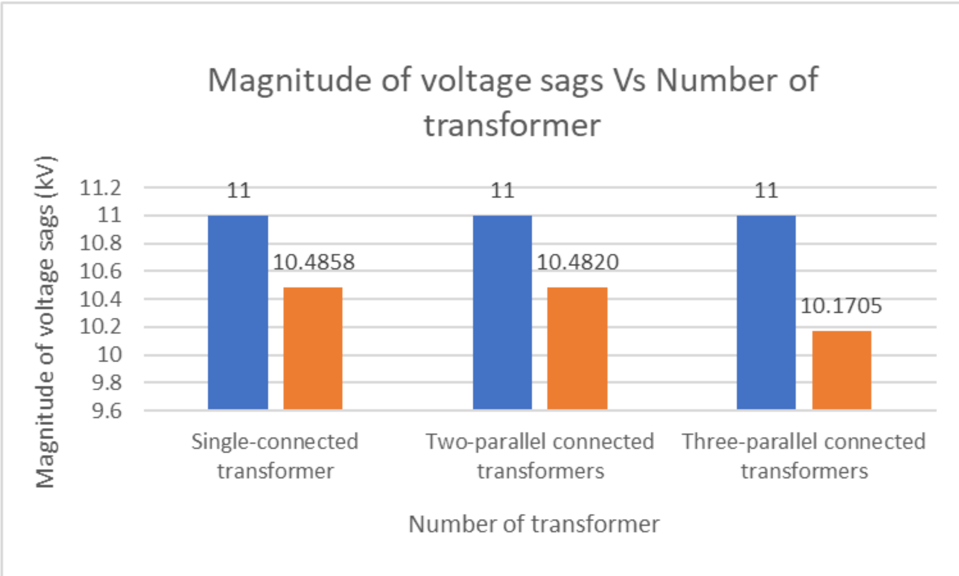

Fig. 12. Comparing voltage reduction from the supplied voltage with varying transformer numbers

4. Conclusions

In a nutshell, this study introduced PSCAD software to model the energisation of 100 KVA, 11 kV/ 415 V transformer as well as all the modelling steps for analysing the inrush current and voltage sags. The objective of this paper is to provide the inrush current phenomenon, the differences between sympathetic and magnetising inrush currents, the fundamental concept of voltage sags, as well as the voltage sags brought on by the energisation of the transformer and a summary of prior works. This paper can assist the researchers to identifying the research gaps in this field. According to early research, by energising multiple transformers can lead the sympathetic inrush current can persist for a longer duration and does not reaching to zero by comparing with magnetising inrush current. Sympathetic inrush currents have an extended settling time since it is related to complicated interactions between numerous parallel-operating transformers in a power distribution network. Additionally, another factors like transformer design, and saturation phenomena also can contribute to the sympathetic inrush current takes a longer times to settle down. Next, the sympathetic inrush current can result in additional issues for a power system, like voltage sags. As presented in this research, there are three different energisation conditions which is single-connected transformer, two-parallel connected transformers, and three-parallel connected transformers. It is possible to obtain the conclusion that by increasing the number of the transformer's energisation, the sympathetic inrush current will be occurred in a high value for the whole system. Not only that, the magnitude is become higher, and the duration of the voltage sags occurs also longer. All these issues can give a big impact to the power system performance which may also harm the electrical equipment. A number of transformer's energisation can be controlled in order to diminish the sympathetic inrush current. In another aspect, it also can improve the functionality and power quality of the system while preventing equipment failure.

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