

Simulation and Analysis Effect of Distribution Transformer Energizing on Electrical Power Quality

Suad Ibrahim Shahl

Abstract— Power transformers are critical components of the electricity networks. The energizing of large power transformers has long been considered a critical event in the operation of an electric power system. When a transformer is energized by the utility, a typical inrush current could be as high as ten times its rated current. This could cause many problems from mechanical stress on transformer windings to harmonics injection, and system protection malfunction. On the other hand, energizing of transformers can also impact the power operation system, by reducing the power quality. Power quality problems caused by transformer energized, is mainly in the form of voltage sag event. Systems of network impedance allocated between the source and energized transformers may experience severe voltage sag. This paper presents transformer energizing MATLAB/Simulink model that is used to simulate various types of voltage sag event. The presented model is used to simulate voltage waveforms for power quality analysis as well as contribute to the studying one of power quality disturbance.

Index Terms— Transformers, Inrush Current, power quality, voltage sag

1 INTRODUCTION

In transmission and distribution systems, transformer energization is a fairly routine operation. However, such an operation may trigger issues such as voltage and current disturbances. The transformer itself is a vital and expensive component of the electricity supply infrastructure. Historically, transformer energization and its associated transients have been investigated in various power system researches. Even though transformer energization issues in transmission and distribution networks are well-known for a long time, the problems are becoming more and more prevalent. This is due to two major factors: (i) the electricity markets have led to an increased number of participants with frequent changes in the network topology, and (ii) the emerging trend globally towards the use of clean renewable energy (wind, solar, etc.) through distributed generation with inherently high degree of intermittency [1].

Transformer energization has given rise to many cases of serious power system issues. In the case of low-frequency transients, transformers frequently encounter the phenomenon of magnetizing inrush current during energizing or post-fault recovery conditions. Although the steady-state magnetizing current is small (typically < 2% of the rated current), its initial inrush transient is very large (>10 times the rated current). This can lead to protection malfunctioning, power quality problems such as voltage sags, and equipment damage from excessive mechanical, thermal and electrical stresses [2].

The inrush current is the maximum, instantaneous input current created by a device when it is first turned on. This phenomenon can be seen in many electrical devices and may result in serious damage of these devices. For this reason, overcurrent protections are usually put in place to protect the device from this harmful inrush current [3]. Research on

transformer energization includes studies on transformer modelling. To investigate inrush—specifically magnetizing or sympathetic inrush—it is necessary to first know how to model the transformer. This paper investigates the inrush transient phenomenon during transformer energization starting from transformer modeling.

2 POWER TRANSFORMER INRUSH CURRENT

Transformers belong to a class of vital and expensive components in a power system. The large power transformers are considered to be important and very expensive asset of electrical power system. They are the static and passive devices for transforming voltage and current. The knowledge of their performance is fundamental in determining system reliability and longevity. They are energised using circuit breakers. In a practical power system, when a transformer is switched on to the line by switching of these circuit breakers, it produces high current in the transformer and cause the circuit breaker to trip or it can blow off the fuse. Another major circumstance were the same situation can arise is when the transformer is on no load with its secondary open. The basic reason for the above mentioned problem is the heavy magnetising current drawn by the transformer. The value of the current may reach a level exceeding the full load current. This current is known as the Inrush Current.

Inrush Current is a form of over current that occurs during energisation of a transformer and is a large transient current which is caused by part cycle saturation of the magnetic core of the transformer. For power transformers, the magnitude of inrush current is initially 6 – 10 times the rated load current. It slowly decreases by the effect of oscillation damping due to winding and magnetising resistance of the transformer as well as the impedance of the system it is connected to, until it reach the normal current value [4]. The excitation characteristics of the transformer core are expressed by the non – linear relationship between the flux and the magnetising current. In the

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steady state the transformers are designed to operate below the knee point of their saturation curve. However, when transformers are energised, due to the effect of inrush current, the flux increases to a high value in the saturation region such that the magnetising current increases drastically. The transformer inrush current is considered to be a critical problem in the practical power systems. Due to its high current it can cause effects like insulation failure, mechanical stress on the transformer windings [5], introduction of power quality issues, and can also affect the sensitive protection devices. The various factors affecting the magnitude of inrush current is [6]:

- The value of residual flux in the transformer core.
- The non – linear magnetising characteristics of the transformer core.
- The phase of the supplying source voltage at the instant of energising the transformer.
- The impedance and short circuit power of the supplying source.

3 INRUSH CURRENTS

Inrush Current, Input Surge Current or Switch – On Surge Current is the maximum, instantaneous input current drawn by an electrical device when it is first turned on. It can last for few cycles of the input waveform. When electrical power transformer runs normally, the flux developed in the core is quadrature with the applied voltage. Inrush current occurs in a transformer whenever the residual flux does not match the instantaneous value of the steady – state flux [7].

For explaining the cause of inrush current in transformers primary winding when connected to an AC voltage source, we consider the equation (1);

$$V = \frac{d\phi}{dt} \quad (1)$$

where ϕ and v are the instantaneous flux in transformer core and voltage drop across the primary winding respectively.

From equation (1), we can understand that the voltage across the transformer primary is proportional to the rate of change of flux in the transformer core. The flux because of the non – linear characteristics of the magnetising curve causes the saturation of the transformer core. The flux waveform can be treated as the integral of the voltage waveform. In a continuously operating transformer, these two waveforms are 90° shifted. When voltage is at zero, the flux waveform will be at its negative peak. This is not the case during energisation of the transformer. At this time, the flux will start from zero.

The figure (1) shows the generation of inrush current in a transformer. As we can see, in certain cases the flux exceeds the knee point resulting in large magnetising current which can be even 10 times as that of the rated current in the transformer.

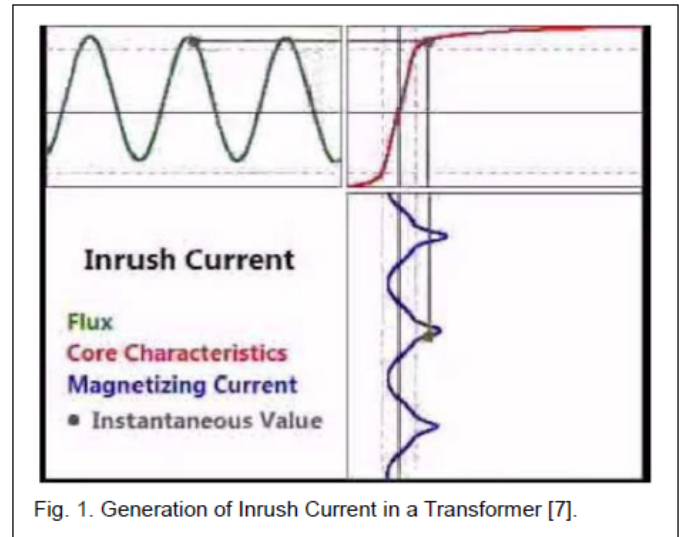


Fig. 1. Generation of Inrush Current in a Transformer [7].

4 TRANSFORMER ENERGIZING MODELING TERMS OF POWER QUALITY

4.1 POWER QUALITY

Electric power systems have today become polluted in industrialized world with unwanted variations in voltage and current. Power quality are primarily issues due to continually increasing sources of disturbances that occur in interconnected power grids, which contain large numbers of power sources, transmission lines, transformers and loads, such systems are exposed to environmental disturbances like lightning strikes. As the numbers of sensitive equipment are increasing in the distribution systems, the voltage quality will become more and more important. The most common power quality problem in industrial distribution systems are the voltage disturbances, which mainly encompasses the voltage sags, swells, harmonics, transients, unbalances, and flickers [8].

Voltage Sag is defined as a short reduction in voltage magnitude for duration of time, and is the most important and commonly occurring power quality issue. The definitions to characterize voltage sag in terms of duration and magnitude vary according to the authority [9]. According to the IEEE defined standard (IEEE Std. 1159, 1995) [10], voltage sag is defined as a decrease of rms voltage from 0.1 to 0.9 per unit (pu), for a duration of 0.5 cycle to 1 minute. Voltage sag is caused by faults on the system, transformer energizing, or heavy load switching.

The study of transformer magnetization inrush phenomena has spanned many decades. When system voltage is applied to a transformer that was previously de-energized, a transient current as high as ten times the rated current occurs for a short period of time before reaching a steady state. This transient current is called the magnetizing inrush current of a transformer, and it is caused by energy transfer that quickly saturates the transformer core. Energization inrush is the most commonly investigated form of inrush. Transformer energization typically draws large inrush currents, which can result in

voltage sags in the power system.

4.2 Voltage Sags

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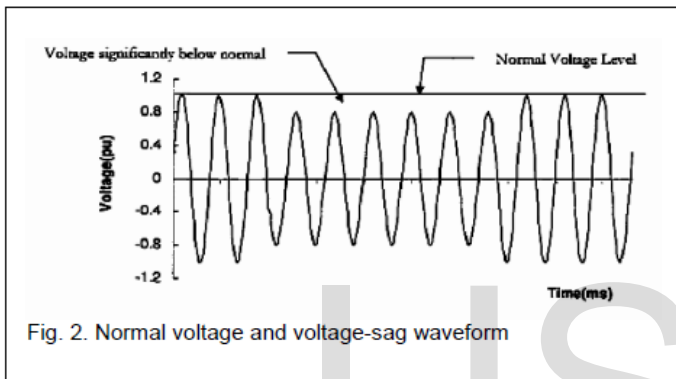


Fig. 2. Normal voltage and voltage-sag waveform

4.3 Voltage Sags Due To Transformer Energizing

The causes for voltage sags due to transformer energizing are [11]:

- Normal system operation, which includes manual energizing of a transformer.
- Reclosing actions

The voltage sags are unsymmetrical in nature, often depicted as a sudden drop in system voltage followed by a slow recovery. The main reason for transformer energizing is the over-fluxing of the transformer core which leads to saturation. Sometimes, for long duration voltage sags, more transformers are driven into saturation. This is called Sympathetic Interaction [12], [13]. Voltage sag can be represented by sinusoidal function and rms voltage profile as shown in Figure 3.

RMS value is calculated from the sine wave voltage with equation 2:

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{i=k} v^2} \tag{2}$$

Where :

N = number of samples per cycle

V_i = sampled voltages in time domain

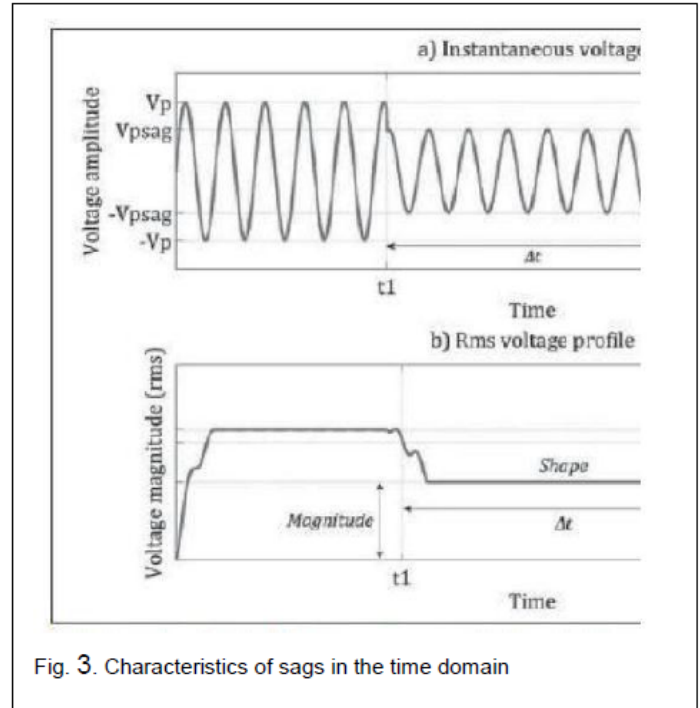


Fig. 3. Characteristics of sags in the time domain

5 SIMULATION RESULTS

This paper studies the voltage sags that occurred during a simulated transformer energizing. The transformer energizing model developed in MATLAB/SIMULINK is shown in Figure 4. It is used to simulate voltage sag caused by transformer in-rush current and core saturation during energizing. The model consists of an:

- 11 kV, 30 MVA, 50 Hz three-phase source block feeding
- Three-phase breaker block
- 11 kV/0.4kV, 1 MVA core transformer block
- 10 kW resistive and 100 VAR inductive loads

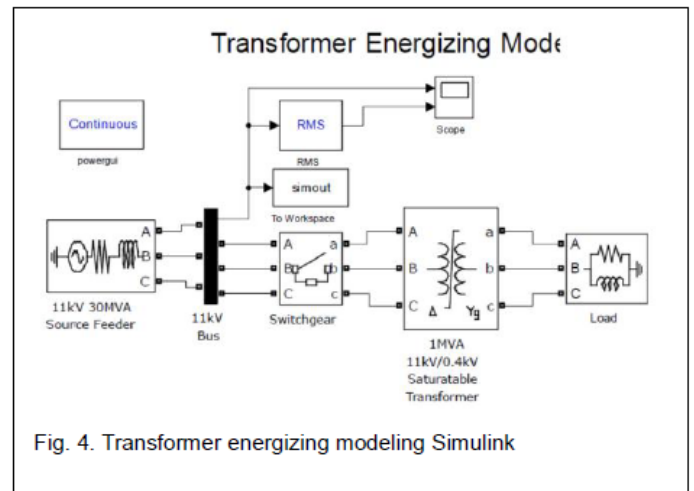


Fig. 4. Transformer energizing modeling Simulink

Figure 5 shows voltage sag due to the energizing of the transformer upon closing of the switchgear that feeds the transformer. All three phases experience unbalanced voltage sag and gradually rise to its nominal voltage level. The measurements of instantaneous waveform and RMS are located at the 11 kV feeder bus.

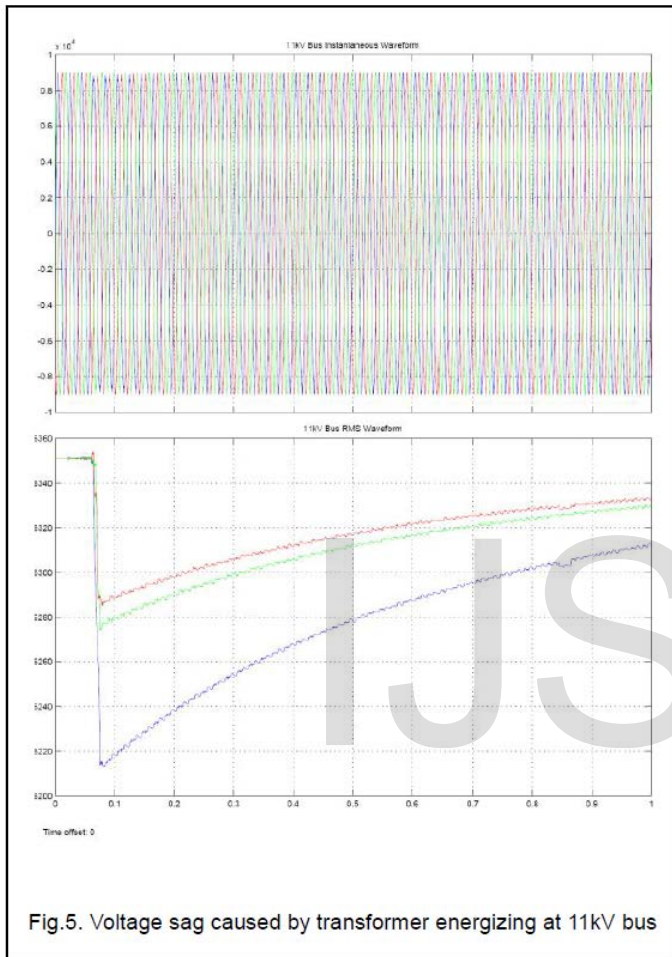


Fig.5. Voltage sag caused by transformer energizing at 11kV bus

The power gui block is used to analyze the harmonic content with the setting of up to 2000 Hz and 10 cycles window. It can analyze up to 40 orders of harmonic content. Figure 6 clearly shows phase A consisting of unusual high 2nd, 6th, 12th, 18th, and 24th order of even harmonic, which is the unique characteristic of transformer energizing voltage sag.

The sag magnitude of the transformer energizing voltage sag is dependent on the source feeder power rating and transformer power rating as shown in Figure 7 and Figure 8.

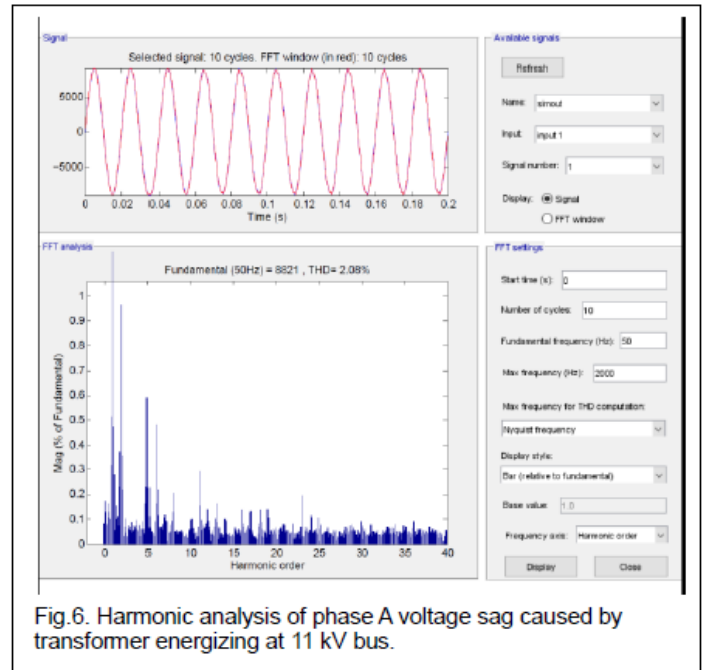


Fig.6. Harmonic analysis of phase A voltage sag caused by transformer energizing at 11 kV bus.

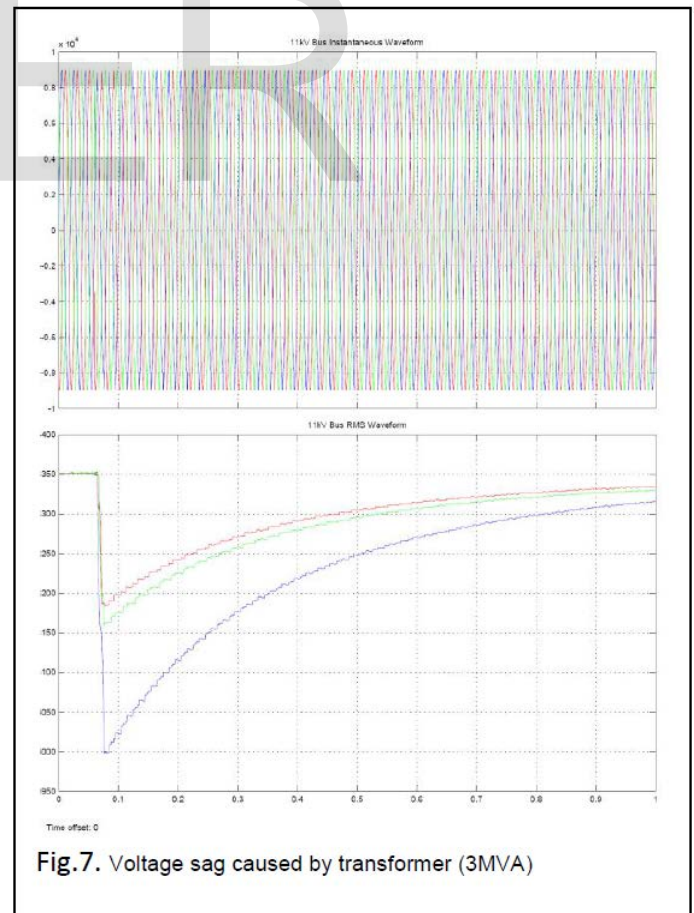


Fig.7. Voltage sag caused by transformer (3MVA)

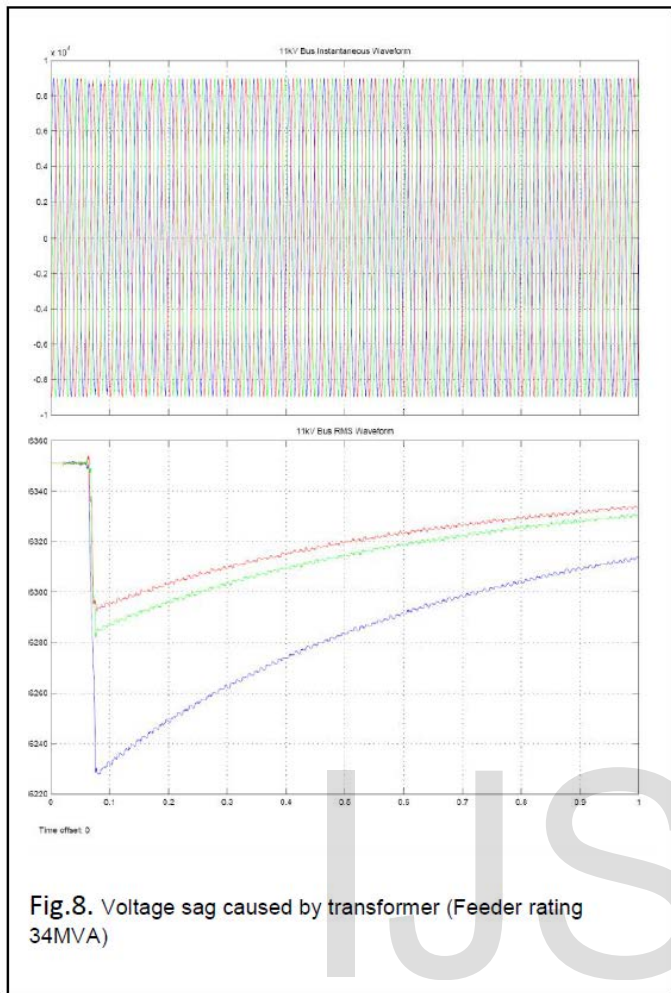


Fig. 8. Voltage sag caused by transformer (Feeder rating 34MVA)

It is clear the higher the transformer power rating, the higher the sag magnitude and the higher source feeder power rating, the lower magnitude.

6 CONCLUSION

Transformers are essential elements, which facilitate the transmission of electric power at high voltages over long distances and transformer energization is a common occurrence. The energization can lead to excessive transient inrush current, especially when the transformer core has remnant flux that adds to the flux build-up after switching. Inrush current sags the system voltage, thereby affecting the power quality of the network in proximity of the transformer. Voltage sag, according to IEEE 1159-1995, is a momentary decrease of 10 to 90 percent in the root-mean square (rms) voltage magnitude for a duration of 0.5 cycles to 1 minute. The unique characteristics of voltage sag caused by transformer energizing are as follows: it is unbalanced, has shallow voltage sag up to 15% from its nominal magnitude, and consists high even harmonic order. Furthermore, the sag magnitude of the transformer ener-

gizing voltage sag is dependent on the source feeder power rating and transformer power rating.

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