TRANSFORMERS

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Contents

Summary

Transformers are used by all power systems for transforming voltage from one level to another. A lot of unnecessary power loss within transmission systems can be reduced if this voltage transformation is optimal. Some transformers are used as auto-transformers if there is no need to isolate the primary and secondary windings in the transformer; it is also well known that auto-transformers are much cheaper than their two windings counterparts, since parts of the windings in auto-transformers are shared by the primary and secondary windings.

In the electrical industry it is common for many large induction motors to use auto-transformers to reduce the motor input voltage during starting, in order to avoid excessive current being drawn from the supply. Whilst there are many successful application examples of using such auto-transformers in conjunction with induction motors during the starting process, there are cases where catastrophic failures have occurred in either the motor or the starting transformer.

This article describes the problems that might arise if an auto-transformer is used to start a high-voltage induction motor rated at hundreds of kilowatts. Readers are therefore reminded of the special attention that should be given to protection arrangements.

1. Introduction

Due to the presence of source impedance, a large electrical machine drawing a high starting current would cause a reduction in the supply voltage for consumers connected to the same supply source. Hence many power companies do not allow voltage drops in excess of 1% of the nominal voltage value upon the starting of a large motor by any single consumer. Many induction motors, particularly those rated at hundreds of kilowatts, must therefore be started at reduced voltage; otherwise the current requirement would be too high when the motor is started direct-on-line, resulting in excessive voltage drops. In many of these arrangements an *open transition* is used. In other words, the induction motor is supplied with a reduced voltage for a short period and the motor windings are then disconnected (opened) from the mains supply temporarily for a short period, after which the reduced supply voltage feeding into the motor is changed to its full value.

Due to the presence of magnetic flux in the air-gap of the motor, there will be an induced voltage in the stator windings, at a frequency dependent on the speed of the motor, during the open-transition period. Upon the application of the full voltage (in other words, at the end of the open-transition period), the stator windings will be subjected to a combination of induced and applied voltage. Depending on the phase shift and the magnitudes of the induced and applied voltages, as well as the frequency of the induced voltage, a very high input motor current might appear and this could lead to the operation of the protection relay, cutting off the power supply to the motor. If this happens the motor would have to be re-started; this is normally very inconvenient for motors rated at hundreds of kilowatts.

In situations where the open transition arrangement during the starting period is not acceptable, it is necessary to arrange the windings so that the motor is energized at all times once the start button has been pressed. Under such arrangement the auto-transformer (if auto-transformers are used to reduce the starting voltage to the motor) would need to operate as a pure inductor for a very short period. If the transformer has not been designed for such a heavy duty, it may fail.

Circuit breakers are required in order to realize the transition from reduced voltage to the full voltage to be applied to the motor windings. It is common to use vacuum circuit breakers because of their compact design and operating effectiveness. However, the inherent ability of vacuum circuit breakers to interrupt the currents abruptly means that there could be a high di/dt in the motor circuit at the time. Hence a high surge voltage could also appear in either the motor and/or the auto-transformer. In fact, it is well known that vacuum circuit breakers can generate a large di/dt when interrupting a small current, compared with a situation when a large current is interrupted. This is because if a large current is flowing in the circuit most vacuum circuit breakers could not, in fact, interrupt it instantaneously. However, it may be possible for the vacuum circuit breaker to interrupt a small current very quickly. Hence if there are no suitable surge arrestors installed for limiting the surge voltage that might appear due to the interruption of inductive currents by the vacuum circuit breaker, a very high transient voltage might emerge across the electrical machine windings when the machine is running on no-load rather than full-load.

This article will consider the possibility that poor earthing arrangements could also be another contributing factor towards cases of auto-transformer failures.

2. Basic Operating Principles of a Transformer

A transformer is used to step up or step down an incoming voltage. In general, the induced voltage per turn ($E_{per\ turn}$) in a transformer is:

$$E_{per\ turn} = 4.44\ f\ \phi \quad \text{where } f \text{ is the frequency and } \phi \text{ is the flux} \qquad (1)$$

Since this is applicable to both the primary and secondary windings, the ratio of the input and output voltage is roughly equal to the ratio of the number of turns in the primary and secondary windings. If a constant supply is connected to the primary winding of a two-winding transformer (in other words, a transformer which has independent primary and secondary windings) then the bigger the ratio of the number of turns in the secondary winding to that of the primary winding, the higher will be the output voltage of the secondary winding.

A two-winding transformer can be reconnected into an auto-transformer by connecting the primary and secondary windings in series, as shown in Figure 1.

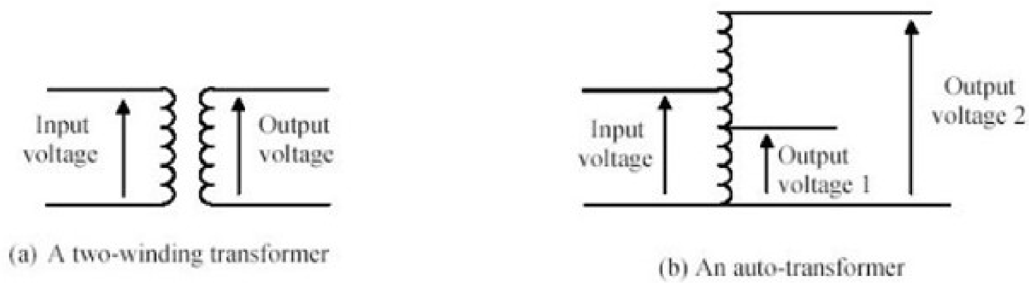

Figure 1. Schematic showing the winding arrangements in transformers

It can be shown that the closer the ratio of the output voltage to the input voltage to unity, the more economical it is to use an auto-transformer. The only drawback of the auto-transformer when compared with its two-windings counterpart is the lack of electrical isolation between the primary and secondary windings.

2.1. Harmonics

Magnetic materials are invariably used in power transformers. The use of high flux densities in the cores of power transformers, due to the constraints of design and size reduction, means that the magnetic circuits are highly saturated. In other words, the value of ϕ in Eq. (1) is high and, because of the non-linear B-H relationship, the magnetizing current waveform will contain a high level of harmonics.

If a transformer is used temporarily as an inductor, as in the case of a no-break starting auto-transformer, then (because of the absence of the demagnetizing current in the core when the auto-transformer functions temporarily as an inductor) the magnetic core will be highly saturated and the current waveform will become very non-sinusoidal.

2.2. Switching Transients

A transformer could be energized with the normal supply and (depending on the instantaneous voltage at which the normal supply is applied) the magnetic flux set up in the transformer could still vary greatly.

For transformers operating at steady state, the back electromotive force (emf), (e), is governed by:

$$e = -\frac{d\phi}{dt} = -\frac{d}{dt}(\phi_m \sin \omega t) = -\omega \phi_m \cos \omega t \qquad (2)$$

where the flux ϕ, which is assumed to vary sinusoidally as a function of time (t), is expressed in terms of its peak instantaneous value ϕ_m and its angular frequency ω. From Eq. (2), it can be seen that the induced emf is lagging between the flux by 90° (electrical). As the magnetizing current is co-phasal with the flux, it can be seen that the induced emf is also lagging behind the magnetizing current by 90° (electrical) at steady state. Since the applied voltage is 180° (electrical) out of phase with the induced emf, one can also conclude that the magnetizing current is 90° (electrical) lagging behind the applied voltage at steady state.

In approximate terms, a transformer could be regarded as a pure inductor at the instant of switch-on. Consequently, one could regard the input current during that instant as being used mainly to magnetize the transformer. If the instantaneous value of the applied voltage at switch-on is the peak voltage, and since the magnetizing current will rise as long as the applied voltage is positive following that instant, the magnetizing current will begin to rise from zero. This will continue for the next 90° (electrical) period for a sinusoidal voltage waveform. After 90° (electrical) the voltage will become negative and the magnetizing current will begin to decrease. In other words, the magnetizing current will lag behind the applied voltage by 90° (electrical), and hence one could infer that the magnetizing current goes straight into steady state. In other words the magnetic flux, which is associated with and is in-phase with the magnetizing current, will be lagging behind the voltage by 90° as well. The back emf is always 180° (electrical) out-of-phase with the supply voltage during the switch-on instant as well as at steady-state.

If the supply voltage is applied at the instant when the supply voltage is beginning to increase from zero, then the magnetizing current will also rise with the voltage at the switch-on instant. Note that the current is supposed to be lagging behind the voltage by 90° at steady state; if the voltage is zero at steady state, then the magnetizing current should reach its negative maximum value. However the current at the switch-on instant is always zero, and if the voltage continues to rise for a 180° (electrical) period the current also will continue to rise during that first 180° period. In other words, the current will not rise for the first 90° (electrical) period and then decrease for the next 90° (electrical) period during the switch-on instant. Thus there is a direct current (DC) offset equal to the instantaneous maximum in the magnetizing current in such cases. The magnetic flux, which is proportional to the magnetizing current, will also start from zero and will have a similar DC offset. Consequently the maximum flux density in the transformer core could be rising towards 200% of its nominal peak magnitude in the first cycle if the applied voltage is switched on when the instantaneous voltage is zero. Such a high magnetic flux value will be associated with a high magnetizing current. This phenomenon is commonly referred as the *doubling effect*. In subsequent half-periods the effect of losses will, however, attenuate the flux rapidly to bring the current and magnetic flux to their corresponding steady state.

Note that if there are remanent fluxes in the transformer yoke, the magnetic flux density could in theory be aiming to reach more than twice its nominal value at the initial stage. This means that the magnetizing current in this case is even higher than in the above-mentioned case where remanent fluxes are not involved. Of course, the magnetic flux could not come close to twice its nominal value because of magnetic saturation, and because the leakage impedance drop in the windings would also limit the magnetizing current to a much lower value. Nonetheless, very high magnetizing currents and very high magnetic fluxes will still appear. As in all cases involving abnormally high magnetic fluxes, the high magnetizing current will produce abnormally high electromagnetic fluxes on the windings.

2.3. Surges

Surge voltage arising from lightning or the operation of vacuum circuit breakers could impact upon system transformers. The surges could have very steep wavefronts, with a rate of rise many times higher than that of the wavefronts encountered when the transformer operates normally. These surge wavefronts would give rise to very high and rapidly changing electric stresses in the transformer windings. It can be shown that most of the surge voltage will appear across the first few turns of the winding during the initial short period when the surge affects the transformer. Most failures in transformers due to surges will therefore appear at the beginning of the winding. Because of this, lightning impulse tests are often carried out on transformers to check whether they are capable of withstanding the high electric field stresses imposed onto the insulation in these circumstances. Essentially the impulses are shaped as shown in Figure 2. The lightning impulse test is not a routine test, however, since a test of this nature would damage the insulation of a transformer to some degree.

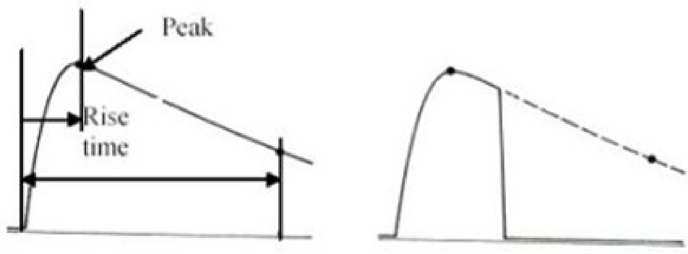

Figure 2. The waveform for the impulse test

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Biographical Sketch

Siu-Lau Ho received B.Sc. and Ph.D. degrees in electrical engineering from the University of Warwick in 1976 and 1979. Since 1979, Prof. Ho has been with the Department of Electrical Engineering, Hong Kong Polytechnic University, where he is now a professor. His current research interests include conditioning, monitoring, and thermal characteristics of electrical machines, and finite-element analysis, as well as meshless methods for design optimization. Prof. Ho is a Chartered Engineer, and a member of the Institution of Electrical Engineers (UK) and of the Hong Kong Institution of Engineers.