A New Method Presentation for Fault Location in Power Transformers

Hossein Mohammadpour, Rahman Dashti

Abstract—Power transformers are among the most important and expensive equipments in the electric power systems. Consequently the transformer protection is an essential part of the system protection. This paper presents a new method for locating transformer winding faults such as turn-to-turn, turn-to-core, turn-to-transformer body, turn-to-earth, and high voltage winding to low voltage winding. In this study the current and voltage signals of input and output terminals of the transformer are measured, which the Fourier transform of measured signals and harmonic analysis determine the fault's location.

Keywords—turn-to-turn faults, short circuit, Fourier transform, harmonic analysis.

I. INTRODUCTION

THE electrical faults of transformers are classified in two types: external and internal faults. External faults are those that occur outside of the transformer: overloads, overvoltage, over-fluxing, under frequency, and external system short circuits. Internal faults are those that occur inside of the transformer: winding phase-to-phase, phase-to-ground, winding inter-turn, over-fluxing, and etc [1].

A very large number of transformers are used in the electric power systems. These costly and critical devices provide the necessary voltage conversions to transfer power through the system. Internal faults in transformers can cause huge damages in a very short time, and in some cases the damages are repairable [2], and also about 70%-80% of transformer failures are caused by internal faults [3]. So fault locating is a necessary work for repairing the faulted transformers, which can be repaired and turned back in service again.

Internal faults especially turn-to-turn faults are common in transformer failures. There are many different techniques available for detecting and/or locating these kinds of faults such as: high frequency analysis [3], Frequency Response Analysis (FRA) [4, 5], Artificial Neural Networks (ANNs) and winding transfer functions [6], finite element analysis [7], online diagnostics of transformer winding insulation failures by Park's vector approach [8], combination of discrete wavelet transforms and back-propagation neural networks [9], experimental studies [10], [11], double Fourier series [12], numerical technique based on symmetrical components [13],

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Genetic Algorithm (GA) [14], and etc. Also transformer model's equivalent circuit is different in each method.

In this paper, the physical model of a 20KV/400V transformer is simulated in MATLAB/Simulink. This transformer model's equivalent circuit considers each of the winding turns separately [4], so simulating and testing the faults in each one of the winding turns or sections is possible. In this equivalent circuit just three turns of each of the primary and secondary windings are modeled, which is a simplified model of windings with *n* turns, and this simplification decreases the process time. Some of the equivalent circuit's elements values are measured from [4] and others are experimental values. All of the mentioned faults are applied in this model one by one in different step times and analyzed. The first step after applying faults on the model is calculating the Fourier transform of the signals. In further analyzes the harmonics and frequency components of all of the faults are extracted from the Fourier transform's plots and are saved as indexes. And the last step is pattern recognition which the fault signals of a real transformer can compared with the saved indexes in the database and the type and location of the fault can be measured.

II. FOURIER TRANSFORM

In this simulation all of the data is generated by the current and voltage signals of input and output terminals of the transformer model's equivalent circuit, one time in no-load mode and another time in with-load mode. No-load mode's scopes obtain three parameters: input voltage, input current, and output voltage. With-load mode's scopes obtain four parameters: input voltage, input current, output voltage, and output current. Each of these scopes' time domain data is saved in a separate table. Both of the no-load and with-load tests are applied once without fault and several times with different types of short circuit faults that mentioned earlier.

When a fault happens, a ripple is generated in the scope's output. These ripples have a very lower frequency band than the waveform, and a variable domain, and it happens in a very short time. After the ripples, the sinusoidal waveform continues, but the waveform's domain is changed: usually voltage domains are decreased and current domains are increased, depends on the number of short circuited turns and location of faults. And also the measured terminal: output or input.

All of the faults are applied in several step times so the fault can occur in different locations of the scopes sinusoidal output waveform. This is so important to have the faults' data in

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different step times because the ripples' domains vary in each point of the waveform. And the worst situations are those that the fault happens in $y=0$ or when it happens in each of the peaks of waveform. In these situations the ripple's domain has the biggest size and usually the ripple's domain is several times bigger than the waveform's domain itself. And the more it is bigger; the more it is dangerous for the transformer. In the firstly simulations (no-load and with-load without applying any of the faults), two step times for each signal is measured (in $y=0$ and in the peak) to apply the faults in these times. There is also important to apply the fault in the simulation after several sinusoidal cycles when the transformer is stable, not running it with a fault at first, because having the ripples values is important for our next analysis.

After simulating all of the faults in both no-load and with-load mode, and running each of the faulted circuit models in MATLAB/Simulink one by one in several step times, each of the waveform output values is saved in a separate table, then there are ready for the next process; The Fourier transform. Fast Fourier Transform (FFT) of each of the voltage and current waveforms is calculated. Then by plotting the absolute value of each of the waveforms' FFT result, faults are diagnosable in the plotted figures.

A. Harmonics and Frequency Components

Power system harmonics are sinusoidal components of periodic waveforms that have frequencies that are multiples of the fundamental frequency of the waveform [15]. For example if the system frequency (fundamental frequency) is *50 Hz*, typical harmonics are odd harmonics such as the third harmonic (*150 Hz*), the fifth harmonic (*250 Hz*), the seventh harmonic (*350 Hz*), and so on. And also the third harmonic is one of the most important harmonics in harmonic analysis of a power system.

The power system's sine form generated voltage and current are defined mathematically as:

$$v(t) = V_m \sin(\omega t) \tag{1}$$

$$i(t) = I_m \sin(\omega t) \tag{2}$$

Where V_m, I_m are the amplitudes of voltage and current waveforms and ω is the angular frequency of the signal ($\omega = 2\pi f = 2\pi (50\ Hz) = 314\ rad/s$ for the frequency of *50 Hz*). All of the noticed equations are related to Linear Time-Invariant (LTI) systems. For dealing better with non-linear electrical systems, engineers use the Fourier theory which says that any periodic waveform can be described as the summation of the series of sine curves with different frequencies and amplitudes [15]. Thus by using the Fourier theory, the periodic pulses of (1) can be modeled as:

$$v(t) = V_0 + V_1 \sin(\omega t) + V_2 \sin(2\omega t) + \ldots + V_n \sin(n\omega t) \tag{3}$$

Which V_0 is the DC value of the waveform, and V_1, V_2, $V_3, \ldots$ are the peak values of the series. The fundamental harmonic (the first harmonic) has the *f* frequency, the second harmonic's frequency is *2f*, and the *n*th harmonic's frequency is *nf*.

In this simulation the frequency components are extracted from the circuit models (the healthy model and all of the faulted models) all in both no-load and with-load mode. Then the harmonics of each signal is extracted from the calculated signal FFTs that mentioned before. And all of the harmonic values are saved in separate tables as indexes for referring to them in cases of real fault for comparison.

B. Fourier Transform Equations

In Fourier analysis the Fourier series are used for processing periodic signals and the Fourier transform is used for processing aperiodic signals. Since the periodic signals of transformer become aperiodic during the fault, we need Fourier transforms for analyzing and processing the signals.

For the aperiodic time-continuous signal of *f(t)* the Fourier transform *g(jω)* is defined as:

$$g(j\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt \tag{4}$$

III. PATTERN RECOGNITION

After saving all of the harmonic indexes separately, all of the studies are ready to be operated practically online in a real transformer. In this step in any case of emergency, if any kind of short circuit faults occur in the transformer, everything is ready for detecting the transformer's fault and the fault's location in a short time. In a real transformer the needed parameters (current and voltage signals of input and output terminals) should be measured and saved so in the case of emergency, the FFT of the measured signals will be calculated in a short time and the harmonics of each one of the signals will be extracted. Now by using pattern recognition, the real fault indexes are compared with the simulated indexes that were saved in a database. Output voltage index in the real transformer will be compared with all of the output voltage indexes of the simulation's database. And also other indexes too (output current, input voltage, and input current). After the comparison is done, kind and the location of fault will be determined.

There is an important factor about the pattern recognition of harmonics that the first harmonic usually has the least faults and the third harmonic index of real transformer signals are the closest values to the database. So in online monitoring we can call off the even harmonics for increasing the comparison speed. With each comparison, some of the indexes that aren't determined as a result will be filtered in the next comparison for speeding up the process.

In an emergency situation when an internal fault happens in an online transformer, as noticed before the FFT of the voltage and current signals of the transformer will be calculated in a short time. And the online transformer's data will be compared to the indexes of the database with this

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function:

$$\sum \left| A(f_{R_i}) - A(f_{S_i}) \right|^2 \qquad (5)$$

IV. SIMULATION RESULTS

The used transformer model as mentioned before has only three turns in each of the windings. So simulating all of the possible short circuit faults in each of the turns and all of the possible turn-to-turn faults are achievable. Each of the single-turn short circuit faults is simulated and all of the possible turn-to-turn faults are simulated too. Other kinds of faults such as turn-to-core, turn-to-transformer body, turn-to-earth, and primary winding to secondary winding are simulated. Primary winding to secondary winding faults are simulated several times too, because each time different primary winding turns are short circuited into different secondary winding turns.

Some of the plotted figures of voltage and current signals' FFTs are represented as samples in below, and list of the simulated faults are showed in "TABLE I" and "TABLE II".

Most of the y axes in the figures are zoomed several times and top the long vertical lines are cut in order that the bottom parts of the figures that are important become visible in the paper.

After simulating all faults, the results are saved in data banks with the calculated indexes of (5). Now if the real fault is occurred, the location of fault must be distinguished. In this method we calculate FFT of voltage and current of real fault and the calculate the special index in (5), then they are compared with several information in data bank and the best matched data is found and is announced as location of fault. In this step, one example is brought. In this example, we suppose a fault is occurred on the second and the third turn of secondary winding. FFT of voltages and currents is shown in "Fig. 5", after calculating the index we receive $V_i=8.63*105$, $I_i=0.14$, $V_o=1254$, $I_o=0.030$ and by comparing these indexes with the saved indexes in the data bank, we'll receive the fault's location between the second and the third turn of secondary winding.
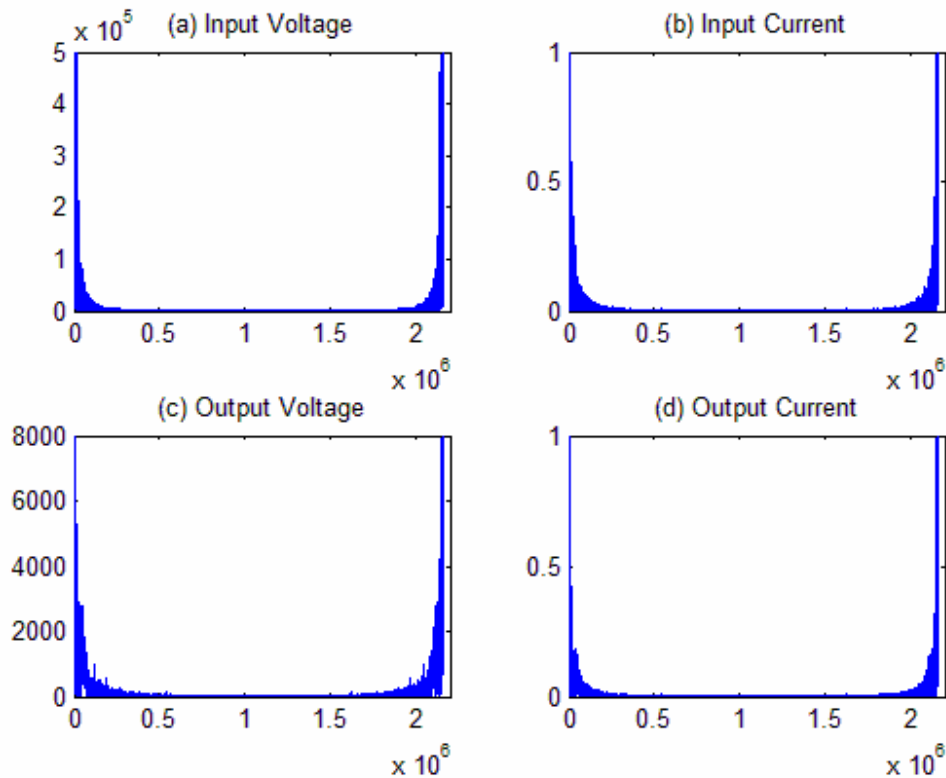

Fig. 1 FFT plot of input and output voltage and current signals in a turn-to-turn short circuit fault between the first and the second turns of the primary winding in with-load mode.

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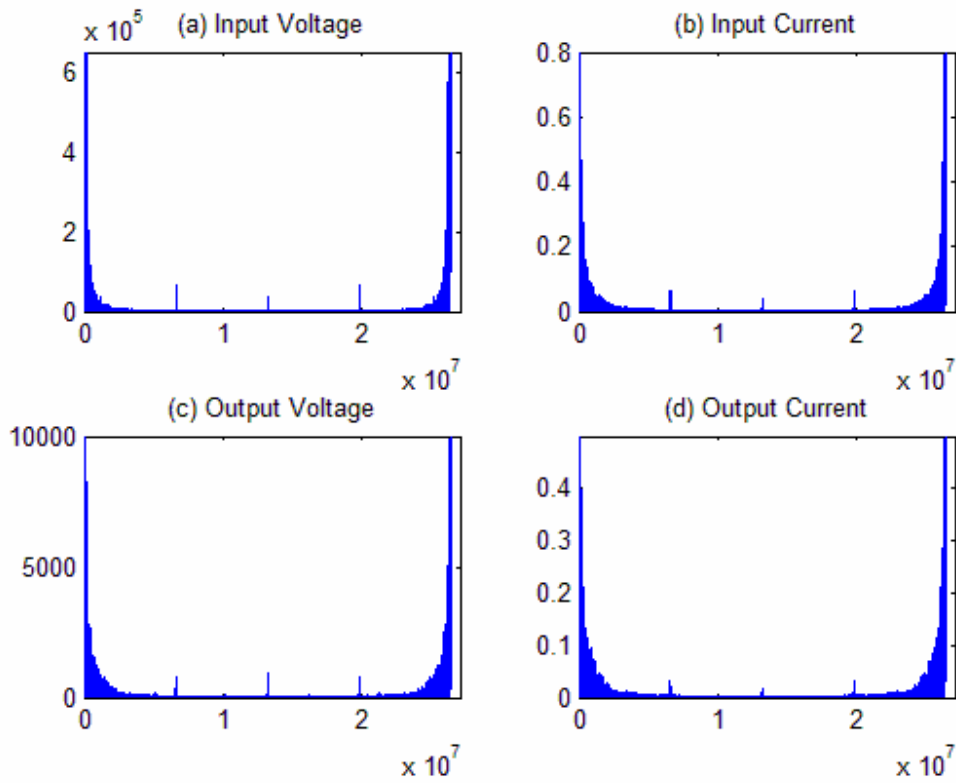International Journal of Electrical and Computer Engineering
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Fig. 2 FFT plot of input and output voltage and current signals in a turn-to-turn short circuit fault between the second and the third turns of the primary winding in with-load mode.
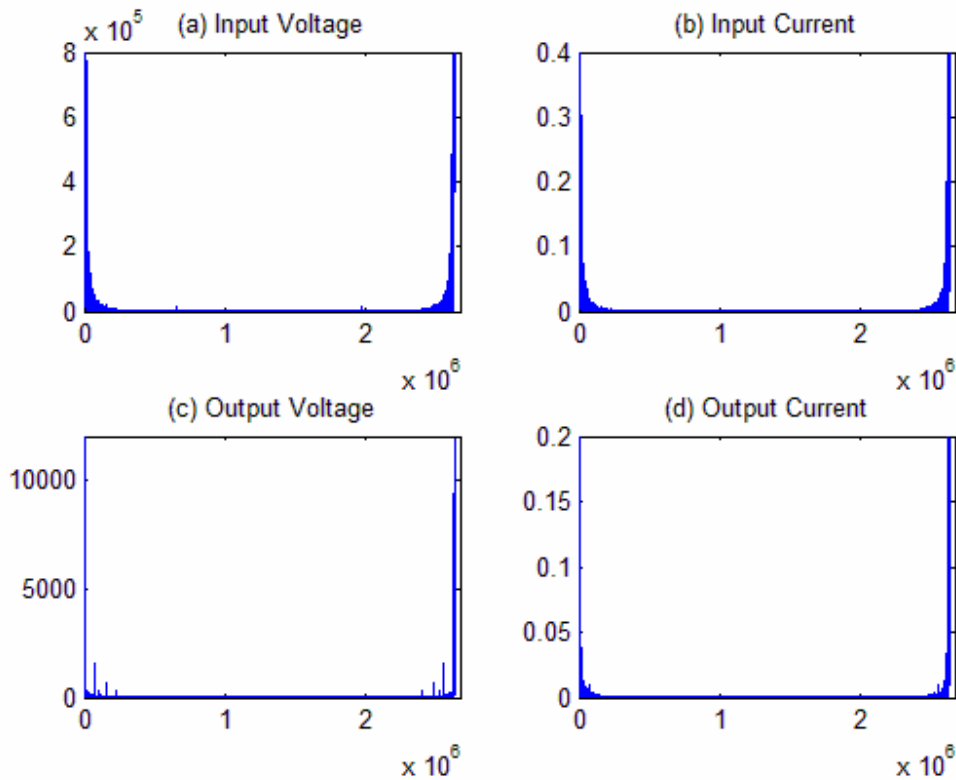
Fig. 3 FFT plot of input and output voltage and current signals in a turn-to-turn short circuit fault between the first and the second turns of the secondary winding in with-load mode.

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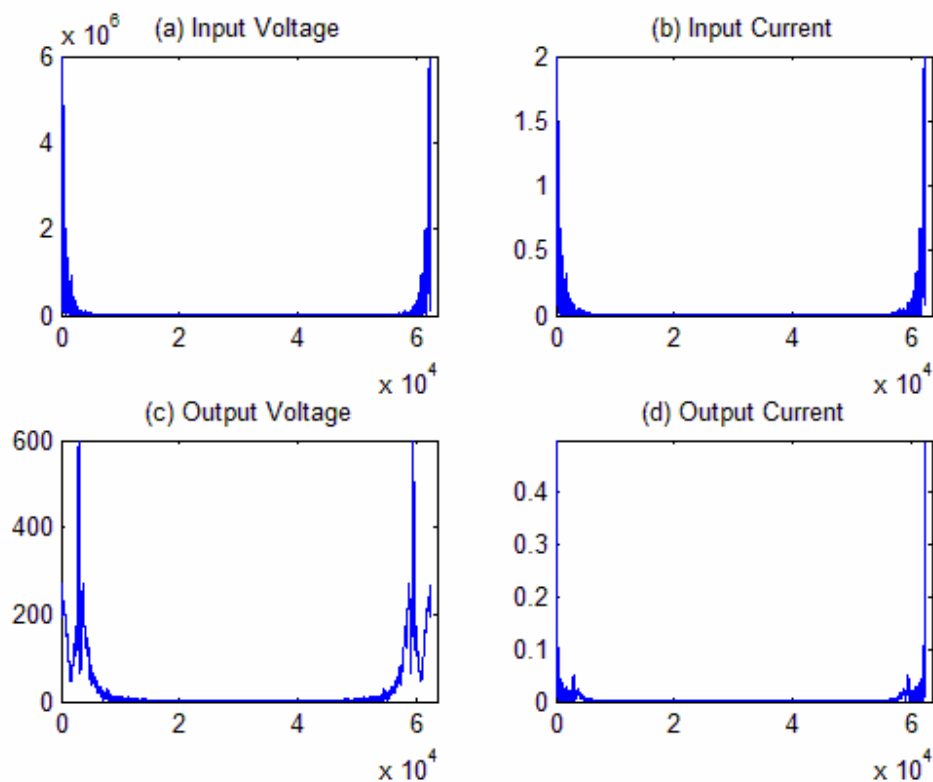International Journal of Electrical and Computer Engineering
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Fig. 4 The first turn of the primary winding is short circuited to the first turn of the secondary winding in with-load mode.
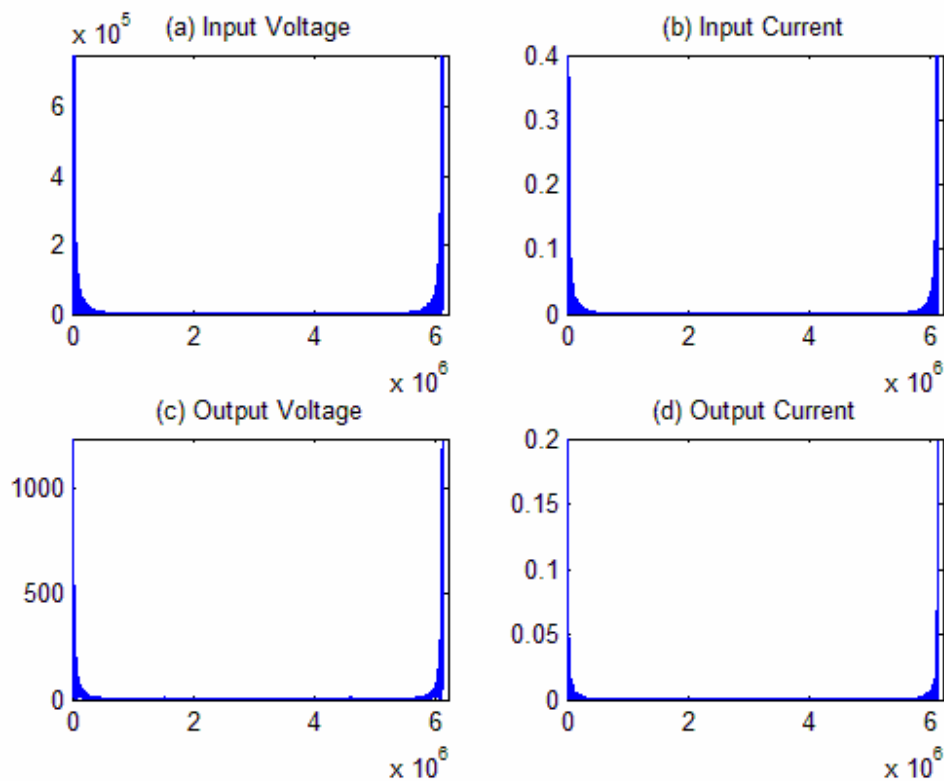

Fig. 5 plot of input and output voltage and current signals in a turn-to-turn short circuit fault between the second and the third turns of the secondary winding in with-load mode.

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V. CONCLUSION

In this paper a simplified model of a power transformer simulated and different kinds of faults applied on it. The frequency components and the harmonics of the FFT signals of all of the simulated faults are extracted and saved as special indexes. The indexes are saved in the database and could be compared with any kind of similar transformer for finding the short circuit fault's location online. This method can also be used for other kinds of internal winding faults too.

TABLE I
SIMULATED TURN-TO-TURN FAULTS

No.	Test Type	Short Circuited Turns	Faulted Winding
1	No-Load	1	Primary
2	No-Load	2	Primary
3	No-Load	3	Primary
4	No-Load	1, 2	Primary
5	No-Load	2, 3	Primary
6	No-Load	1, 2, 3	Primary
7	No-Load	1	Secondary
8	No-Load	2	Secondary
9	No-Load	3	Secondary
10	No-Load	1, 2	Secondary
11	No-Load	2, 3	Secondary
12	No-Load	1, 2, 3	Secondary
13	With-Load	1	Primary
14	With-Load	2	Primary
15	With-Load	3	Primary
16	With-Load	1, 2	Primary
17	With-Load	2, 3	Primary
18	With-Load	1, 2, 3	Primary
19	With-Load	1	Secondary
20	With-Load	2	Secondary
21	With-Load	3	Secondary
22	With-Load	1, 2	Secondary
23	With-Load	2, 3	Secondary
24	With-Load	1, 2, 3	Secondary

TABLE II
SIMULATED PRIMARY WINDING TO SECONDARY WINDING SHORT CIRCUIT FAULTS

No.	Test Type	Short Circuited Turns
1	No-Load	1st turn of primary to 1st turn of secondary
2	No-Load	1st turn of primary to 2nd turn of secondary
3	No-Load	1st turn of primary to 3rd turn of secondary
4	No-Load	2nd turn of primary to 1st turn of secondary
5	No-Load	2nd turn of primary to 2nd turn of secondary
6	No-Load	2nd turn of primary to 3rd turn of secondary
7	No-Load	3rd turn of primary to 1st turn of secondary
8	No-Load	3rd turn of primary to 2nd turn of secondary
9	No-Load	3rd turn of primary to 3rd turn of secondary
10	With-Load	1st turn of primary to 1st turn of secondary
11	With-Load	1st turn of primary to 2nd turn of secondary
12	With-Load	1st turn of primary to 3rd turn of secondary
13	With-Load	2nd turn of primary to 1st turn of secondary
14	With-Load	2nd turn of primary to 2nd turn of secondary
15	With-Load	2nd turn of primary to 3rd turn of secondary
16	With-Load	3nd turn of primary to 1rd turn of secondary
17	With-Load	3nd turn of primary to 2rd turn of secondary
18	With-Load	3nd turn of primary to 3rd turn of secondary

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