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Prevention of False Operation of Distance Relay in Ferroresonance

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ABSTRACT: Ferroresonance is one of the main causes of failures in electrical network. It results in increasing the magnitude of voltage and current, which causes operation of protective relays. Impedance measured by distance relay is deviated in effect of Ferroresonance; furthermore, swing behaviour of power and impedance in effect of Ferroresonance causes operation of OSB (Out of Step Blocking) element of distance relay; hence, operation of relay is blocked. In this paper, Ferroresonant states are examined in Manitoba Hydro 230 kV electrical network by means of PSCAD/EMTDC. Ferroresonance is detected by means of visual detection tools. Effect of Ferroresonance on distance relay and OSB element is analyzed. An adaptive Logical algorithm, which is based on THD (Total Harmonic Distortion) and Fr.d (Frequency deviation) measurement in time domain, is implemented in the software. Ferroresonant states are re-examined in presence of the logical algorithm in distance relay to prevent mal-operation of the relay; furthermore, stability domain boundary of voltage based on THD and frequency deviation is specified by the algorithm in the network.

KEYWORDS: distance relay, Ferroresonance, Ferroresonance detection algorithm, Manitoba Hydro, OSB element, PSCAD/EMTDC, stability domain boundary, time domain analysis

I. INTRODUCTION

Distance relay with OSB element comprises harmonic filter to use fundamental waveform of parameters and eliminates interferences. In case of occurring severe Ferroresonance, the magnitude of parameters increases, whereas fundamental waveform of parameters decreases with respect to total magnitude due to increasing magnitude of harmonics. It results in over and under reaching of distance relay. In addition, Ferroresonance causes frequency deviation, which depends on magnitude and phase of harmonics with respect to fundamental. It results in frequency difference between two points in the network and power oscillation. Distance characteristic is surrounded by inner and outer circles of OSB scheme. In power swing due to Ferroresonance, Impedance locus traverses across OSB elements and operation of relay is blocked.

Ferroresonant states can be detected according to their certain characteristics; hence, Ferroresonance analysis tools in time domain can specify Ferroresonance modes; furthermore, it will be shown that, stability domain boundaries can be specified by means of criteria in time domain. It is the advantage of using Ferroresonance detection algorithm to determine stability domain boundaries in normal operation to warn risk of Ferroresonance; furthermore, making a decision on behaviour of distance relay in Ferroresonance according to protection strategy.

In this paper, theoretical analysis of distance relay with OSB element is represented and then practical analysis of Ferroresonance in time domain is performed to design a logical algorithm in distance relay to distinguish between normal and Ferroresonant states and prevent mal-operation of the relay. Furthermore, a case study is implemented to present Ferroresonant states in the network.

Manitoba Hydro 230 kV electrical network has experienced Ferroresonant states; hence, it is chosen to study Ferroresonance and operation of distance relay in the network. Manitoba Hydro with several plants and substations like constant source, generator, and transformer is simulated in the software to analyse Ferroresonance in presence of different types of elements in the network. In this study, two Ferroresonant states are examined in the network to study operation of distance relay, which employs Ferroresonance detection algorithm to determine Ferroresonance modes and stability domain boundary of the voltage.

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II. OPERATIONAL ASPECT OF DISTANCE RELAY WITH OSB ELEMENT

Distance relay measures voltage $U_L(t)$, current $I_L(t)$ and $\frac{dI_L(t)}{dt}$ at two successive instances in time and compiling the equation as follow.

$$U_L(t) = R_L.I_L(t) + L_L\frac{dI_L(t)}{dt} \qquad (1)$$

By obtaining two successive of $U_L(t_1)$,$U_L(t_2)$ and $I_L(t_1)$, $I_L(t_2)$ then solving the set of equations, $R_L$and L_L are calculated as follow.

$$L_L = \frac{U_L(t_1).I_L(t_2) - U_L(t_2).I_L(t_1)}{\frac{dI_L(t_1)}{dt}.I_L(t_2) - \frac{dI_L(t_2)}{dt}.I_L(t_1)} \qquad (2)$$

$$R_L = \frac{\frac{dI_L(t_2)}{dt}.U_L(t_1) - \frac{dI_L(t_1)}{dt}.U_L(t_2)}{\frac{dI_L(t_1)}{dt}.I_L(t_2) - \frac{dI_L(t_2)}{dt}.I_L(t_1)} \qquad (3)$$

In order to eliminate transient oscillations and interferences due to line capacitances, series compensation, and saturation of instrument transformers, which are not considered by the *R-L* replica of the line, filtering is required in digital relays. Advanced distance relays use digital FIR (Finite Impulse Response) filters. Measurement is done by evaluation of samples, which are taken with specific sampling interval in a time window.

Fourier filtering technique is used to evaluate fundamental frequency. At first, voltage and current are transformed in to phasor quantities (respective real and imaginary components) by orthogonal filters as stated in (4) and (5). The principle is discussed using a Fourier filter with full period integration length (data window of one period).

$$Re\{P\} = \frac{1}{T_N}\int_{\frac{-T_N}{2}}^{\frac{+T_N}{2}} P_L(t)\,cos(\omega_N t)\,dt \qquad (4)$$

$$Im\{P\} = \frac{1}{T_N}\int_{\frac{-T_N}{2}}^{\frac{+T_N}{2}} P_L(t)\,sin(\omega_N t)\,dt \qquad (5)$$

Where:

$P_L = U_L, I_L$is replaced as voltage or current in equations for simplicity.

$\omega_N = 2\pi f_N$

T_N = period of fundamental

The complex value of the phasor is:

$$P_L = Re\{P_L\} + jIm\{P_L\} \qquad (6)$$

From the above calculations, the following formulas are obtained for $R_L$and X_L

$$X_L = \frac{Im\{U_L\}.Re\{I_L\} - Im\{I_L\}.Re\{U_L\}}{Re\{I_L\}^2 + Im\{I_L\}^2} \qquad (7)$$

$$R_L = \frac{Re\{U_L\}.Re\{I_L\} + Im\{U_L\}.Im\{I_L\}}{Re\{I_L\}^2 + Im\{I_L\}^2} \qquad (8)$$

The phasor quantities are defined in polar and trigonometric form respectively as follow.

$$P_L = P_L.e^{j(\omega t + \varphi_P)} \qquad (9)$$

$$P_L = P_L[\cos(\omega t + \varphi_P) + jsin(\omega t + \varphi_P)] \qquad (10)$$

By inserting equation (9) in (7) and (8); in addition, applying the sum and difference trigonometric functions the following equations are obtained [2] [3].

$$X_L = \frac{U_L.\sin(\varphi_U - \varphi_I)}{I_L} \qquad (11)$$

$$R_L = \frac{U_L.\cos(\varphi_U - \varphi_I)}{I_L} \qquad (12)$$

Nevertheless, distance relay is susceptible to mal-operation in case of arc resistance, intermediate in-feed or mutual impedance in parallel lines [1]. Furthermore, increasing the magnitude of measured parameters for instance, in Ferroresonant states (will be shown in section IV.*B*) causes significantly low measurement of impedance with respect to actual line impedance even in non-resistive three phase faults. It results in transient overreach in first zone and sustained overreach in second zone whereas, no fault occurs in the network.

Percent overreach due to offset current wave is defined in [4]. The same formula can be generalized in Ferroresonance when a Ferroresonant state is detected. This is presented by the following formula.

$$Overreach\% = \frac{Z_F - Z_S}{Z_S} \tag{13}$$

Where:

Z_F = the maximum impedance for which the relay will operate in Ferroresonant state for a given adjustment.

Z_S = the maximum impedance for which the relay will operate in no-Ferroresonant state in case of fault currents for the same adjustment as for Z_F.

In order to prevent false operation of distance relay in power swing, Protective zones are surrounded by OSB scheme. The scheme includes outer and inner elements. Impedance locus passes through OSB elements in power swing. It is calculated by the following formulas [5].

$$R + jX = Z = \frac{V}{I} = \frac{X_T}{2}.\cot\left(\frac{\delta}{2}\right) \tag{14}$$

$$\frac{dz}{dt} = -\frac{X_T}{2} \cdot \left(\frac{1}{1-cos\delta}\right).\left(\frac{d\delta}{dt}\right) \tag{15}$$

Where:

X_T= total impedance of the system

δ = load angle

Furthermore, a power swing detection algorithm, which is based on a curve-fitting model of a power swing, is used to detect power oscillation. The model is described by the following formula for each extrema of the signal in Fig. 1 [6].

$$S(t) = X + A_0 e^{\delta t} \sin\left(\frac{2\pi t}{T}\right) \tag{16}$$

Where:

X = mean value of the signal

A_0 = start value of the amplitude

δ = time constant of the envelope

T = time between two maxima

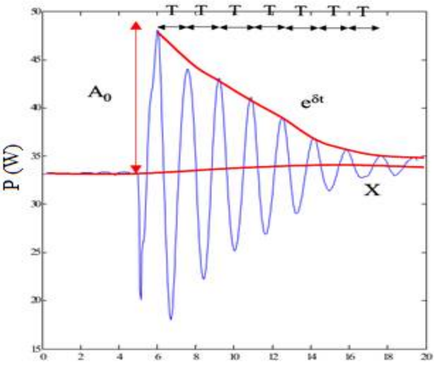


Fig. 1. Power swing model.

According to above mentioned formulas and algorithms, OSB element detects any similar oscillation in effect of various phenomena in the network. Electrical network with non-linear elements and considerable values of capacitance causes Ferroresonance, which deviates frequency of misshaped waveform from nominal value. The value of frequency in Ferroresonance depends on value and phase of harmonics with respect to fundamental. The values and characteristics of non-linear elements in different stations and lines in the network can be different; hence, the value of frequency can also be different in different stations. As will be shown in section IV.*A*, Ferroresonance causes frequency difference among stations and power oscillation in the network. Impedance locus traverses across OSB elements and blocks operation of distance relay.

III. TIME DOMAIN ANALYSIS OF FERRORESONANCE IN DISTANCE RELAY

A graphical approach is obtained by calculating the parameters of nonlinear circuits in time domain. For instance, in a typical series RLC circuit (Fig. 2) inductor voltage is calculated as follow [7].

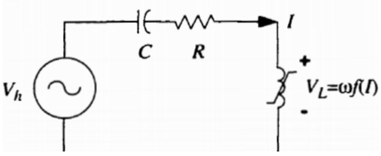


Fig. 2. Series RLC Ferroresonant circuit example.

$$V_L = \sqrt{V_h^2 - (I.R)^2} + \frac{I}{\omega C} \qquad (17)$$

It is also a nonlinear function of current as follow.

$$V_L = \omega f(I) \qquad (18)$$

As was mentioned above, frequency of waveform can be deviated from nominal frequency in Ferroresonance so that frequency deviation can be defined as follow.

$$Fr.d = |F_{Fr} - F_{nom}| \qquad (19)$$

Where:

F_{Fr} = frequency of waveform in Ferroresonance

Resulted waveform is decomposed to its number of harmonics using FFT (Fast Fourier Transform). Measurement is done by evaluation of samples, which are taken in specific sampling interval; hence, discrete Fourier Transform is used with a certain sampling rate to illustrate harmonic components on harmonic spectrum.

$$V_{Lk} = \sum_{n=0}^{N-1} V_{Ln} e^{-j2\pi k\frac{n}{N}} \qquad K = 0 \ldots N-1 \qquad (20)$$

N = number of samples

Then, Total Harmonic Distortion is calculated so integer Harmonics, which obtained from FFT, are considered in the following formula [8].

$$THD = \sqrt{\sum_{h=2}^{x} \left(\frac{individual\ (h)}{individual\ (1)}\right)^2} \qquad (21)$$

x = integer harmonics

In order to determine Ferroresonance based on measurement in a logical circuit, Ferroresonant characteristics must be quantified. THD and Fr.d are the quantities, which are used as criteria to determine Ferroresonance of different types (Table 1).

Ferroresonance Type	Fr. d	$\frac{dFr.d}{dt}$	T.H.D (%)	Harmonic spectrum
Fundamental	zero	zero	50 <	Discrete
harmonic	constant	zero	50 <	Discrete
Quasi-periodic	variable	Not zero	100 <	Discrete
chaotic	variable	Not zero	100 <	Continuous

Table 1: criteria to determine Ferroresonance modes.

Fundamental Ferroresonance is detected when frequency of waveform remains at nominal value (Fr.d is zero) and the value of THD is more than 50%. Harmonic Ferroresonance is detected when frequency of waveform is deviated from nominal value and remains constant (Fr. d is not zero); furthermore, the value of THD is also more than 50%. In most cases, fundamental and harmonic Ferroresonance contain odd harmonics; hence, harmonic spectrum is discrete. Quasi-periodic and chaotic modes are determined when $\frac{dFr.d}{dt}$ is detected and calculated as follow.

$$\frac{dFr.d}{dt} = T.\frac{Fr.d(t)-Fr.d(t-\Delta t)}{\Delta t} \qquad (22)$$

Where:
T = time constant
$t - \Delta t$ = previous time step
Δt = time step interval

Furthermore, the value of THD increases more than 100% where chaotic mode contains a continuous harmonic spectrum. As harmonic spectrum is mostly a qualified characteristic, THD and Fr.d are used in logical circuit to determine Ferroresonance modes.

The logical algorithm is used in distance relay to distinguish Ferroresonance states. It is able to block, extend, or restrict operating characteristics; furthermore, it changes operating time of the characteristics according to type of Ferroresonance and protection scheme.

Fig. 3 shows an example of flowchart of Ferroresonance detection algorithm, which shift operating zones (zones 1 and 2) of distance relay with mho characteristics and OSB elements (inner and outer characteristics) in Ferroresonant states. The algorithm takes setting parameters of the relay and measures grid parameters like voltage, current, frequency, and load angle and then calculates impedance, $\frac{\mathrm{dz}}{\mathrm{dt}}$, Fr.d, THD, and $\frac{\mathrm{dFr.d}}{\mathrm{dt}}$. In case of detection of out of step conditions along with Ferroresonance, the algorithm pursues impedance locus. In order to determine new setting value of inner characteristic it measures maximum and minimum values of R and X and then changes the radius of the inner circle by multiplying a Security Factor (SF) to the measured value to increase stability margin. Radius of outer characteristic is always determined by multiplying a K factor to the value of radius of inner characteristic. Similarly, when pickup value of protective zones is detected along with Ferroresonance, the algorithm measures minimum value of impedance so that new setting value of radius of the characteristic is calculated by multiplying a Security Factor (SF) to the measured value to increase stability margin. It results in restriction of protective zone. If changing the radius is not effective, the algorithm changes center of the characteristic so that impedance locus traverses out of the protective zones. To do so, both measured values of R and X are negated and multiplied by a security factor (SF) to keep away from trip values of impedances. In such cases center of OSB elements follows center of Z2 to enclose both protective zones.

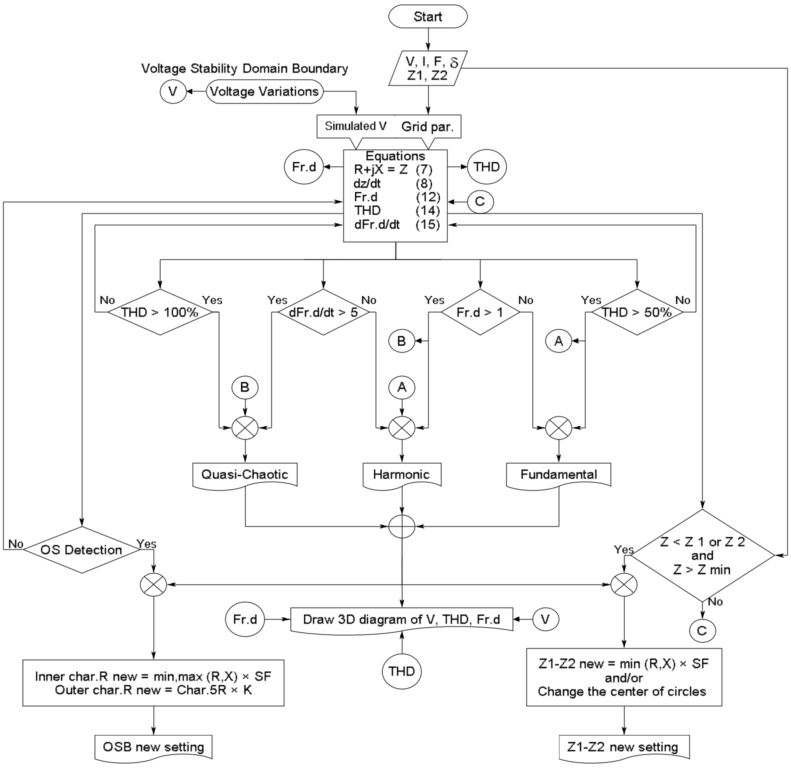


Fig. 3. Flowchart of logical Ferroresonance detection algorithm.

It must be noted that consideration of maximum or minimum R, X value of impedance locus to set the radius of circles and location of OSB elements is taken so to prevent confliction and over lapping with protective zones.
It also is notified that the advantage of shifting operating characteristic instead of blocking the relay in case of Ferroresonance is just consideration of specific features of impedance loci experienced in Ferroresonant states, whereas the relay must be responsible in case of $Z < Z_{min}$ which imply on catastrophic states. The value of Z_{min} is determined according to protection scheme.
In addition, the algorithm is able to determine stability domain boundaries of parameters based on the value of THD and Fr.d. It is established when desired parameter is simulated and ramped versus the values of THD and Fr.d. For instance, stability domain boundary of voltage is obtained by the algorithm in Fig. 3. In addition, types of Ferroresonance are determined in each value of voltage. This characteristic can be calculated by the relay in normal operation to warn risk of Ferroresonance in the same network configuration.

IV. FERRORESONANT STATES IN THE NETWORK

Several Ferroresonant states have been reported in Manitoba Hydro 230 kV electrical network; hence, it is a good example of Ferroresonant studies [7] [10] [11]. For instance, a voltage transformer failed due to opening grading capacitor circuit breakers at the Dorsey converter station in 1995. In addition, the network has been under investigation in order to find Ferroresonant state which causes power oscillation like, transformer-terminated double circuit line study, which is mentioned in [12]. It is re-examined in this study to illustrate mal-operation of OSB element in distance relay to examine adaptive detection algorithm in Ferroresonance to stabilize the relay. In this study, Manitoba Hydro electrical network includes several 230 kV stations as equivalent source like; Vermillion, Dorsey, Ridgway, Rosser; in addition, Grand Rapids is simulated as both generator and equivalent source [13]. Ashern station at the middle of the network comprises a damping reactor, (is out of service in this study) which connects Grand Rapids to Rosser station via (G1A-G2A at Grand Rapids end and A3R-A4D at Rosser end) 500 km double circuit transmission lines. Furthermore, Silver station comprises two transformers, which are supplied from the double circuit line (Silver tap Fig. 4). Distance relay is examined in this station to represent application of Ferroresonance detection algorithm. Some stations in the network are shown in Fig. 4.

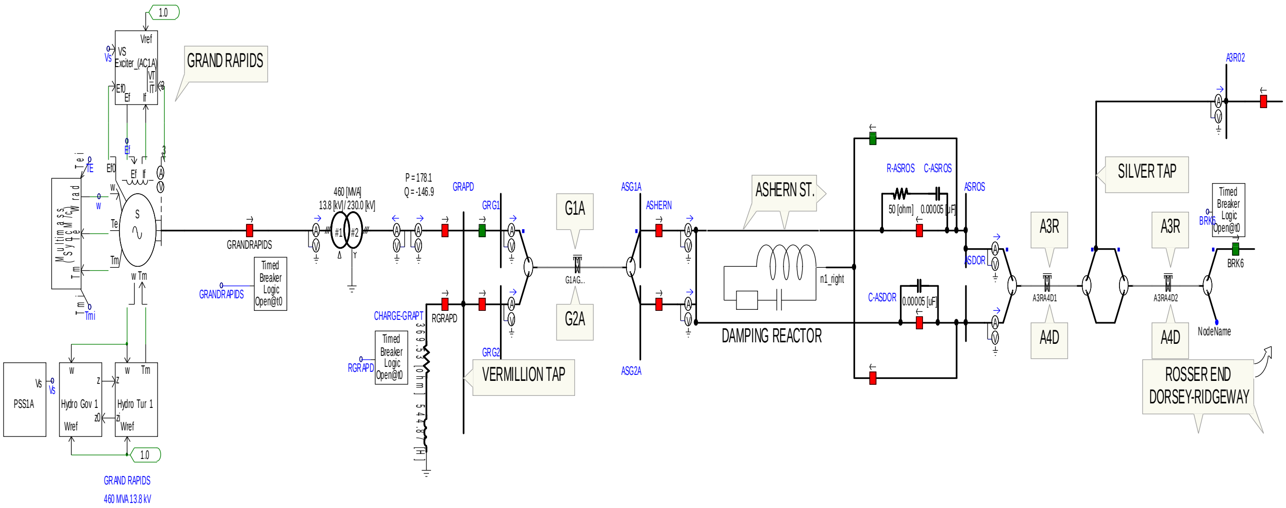


Fig. 4. Part of Manitoba Hydro network under study in PSCAD/EMTDC.

In order to investigate impact of Ferroresonance on distance relay and application of Ferroresonance detection algorithms in the relay, two Ferroresonant states are represented as follow.

A. *Ferroresonance in case of changing line arrangement*

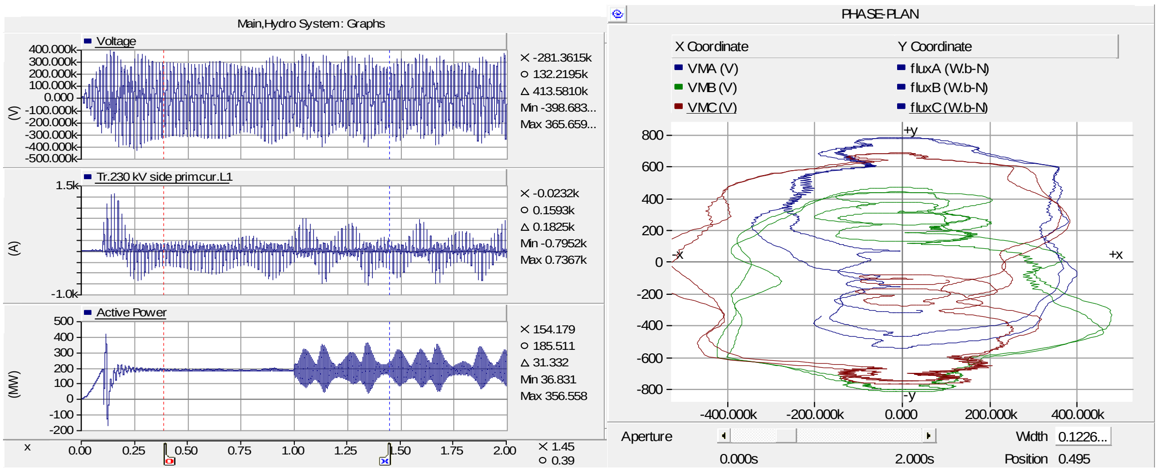
Changing line arrangement in the network might lead in configuration, which causes Ferroresonance. One of the most probable Ferroresonant configurations results of changing line arrangement is formed when a double circuit transmission line is terminated by a transformer. Capacitive coupling between double circuit lines and saturable iron core of transformer makes a Ferroresonant circuit.

In order to emerge Ferroresonance, many statuses are examined. In all statuses, both lines are remained energized. Hence, capacitive coupling of lines is not the only reason of occurring Ferroresonance.

The Ferroresonance mentioned above has been completely explained in [9]; hence, the results of simulation, which can be used in this paper, are briefly explained as follow.

In case of changing arrangement by opening green breakers (Fig. 4), A3R and G1A lines are changed to an open-end line whose voltage is increased and causes saturation of transformer. It results in increasing and misshaping voltage and current in Silver station (Fig. 5a).As it was mentioned in advance, due to variety of non-linear characteristics in the network, the value of frequency may vary in different places. It causes power oscillation in the network. Fig. 5b shows oscillation of power in Grand Rapids station in both equivalent source and generator modes. Magnitude of power variations in equivalent source mode is about 178-204 MW with a frequency of about 10 Hz. The magnitude and frequency of power variations are increased in generator mode (80-320 MW, 16 Hz).

Fig. 5b shows phase plan diagram after Ferroresonance. Ferroresonant states can be distinguished in Phase plan diagram. Diagram plots voltage versus flux. The circles are misshaped in Ferroresonance so that more severe Ferroresonance results in more misshaped circles. Time division of the plot is set to nominal frequency. The circles are not repeated in each time division in non-periodic Ferroresonance



(a) (b)

Fig. 5. Ferroresonance in case of changing line arrangement. (a) Oscillation of electrical parameters, (b) phase plan diagram.

Fig 6 shows impedance loci, which oscillate across OSB elements. The area of oscillation is determined by values of fundamental components of voltage and current, which calculate impedance. Operation of protective zones is blocked in this condition.

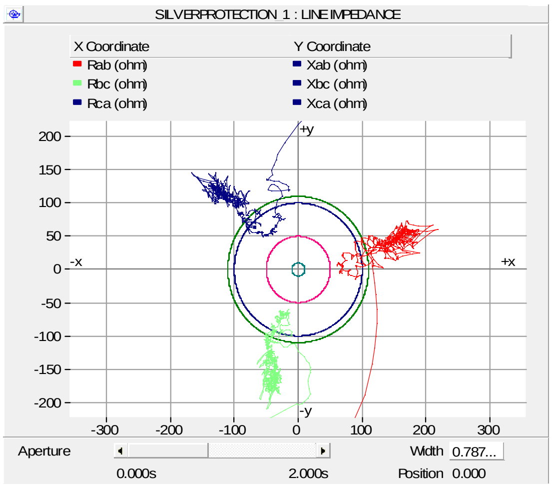
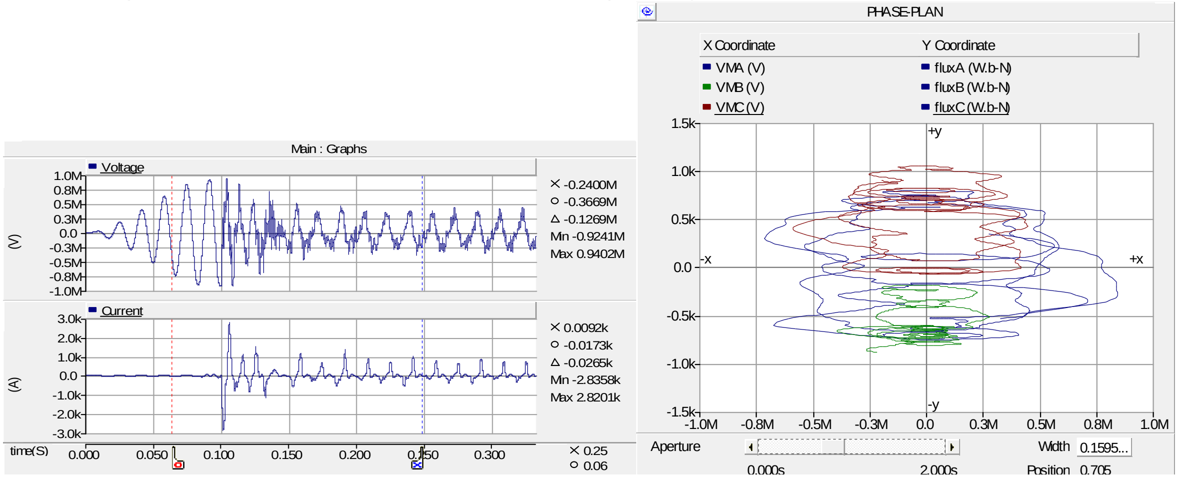


Fig. 6.Oscillation of impedance loci in Ferroresonance in case of changing line arrangement.

B. *Ferroresonance in case of plant outage*

Scheduled or accidental plant outage is an ordinary operation, which takes place in power networks. Plant outage changes some electrical parameters in the network such as sum of R-L-C values; furthermore, it changes load flow and power distribution. In some cases, plant outage may change the magnitude of voltage so that causes saturation of iron core in transformers and reactors. Therefore, plant outage will be able to make a configuration, which leads in Ferroresonance.

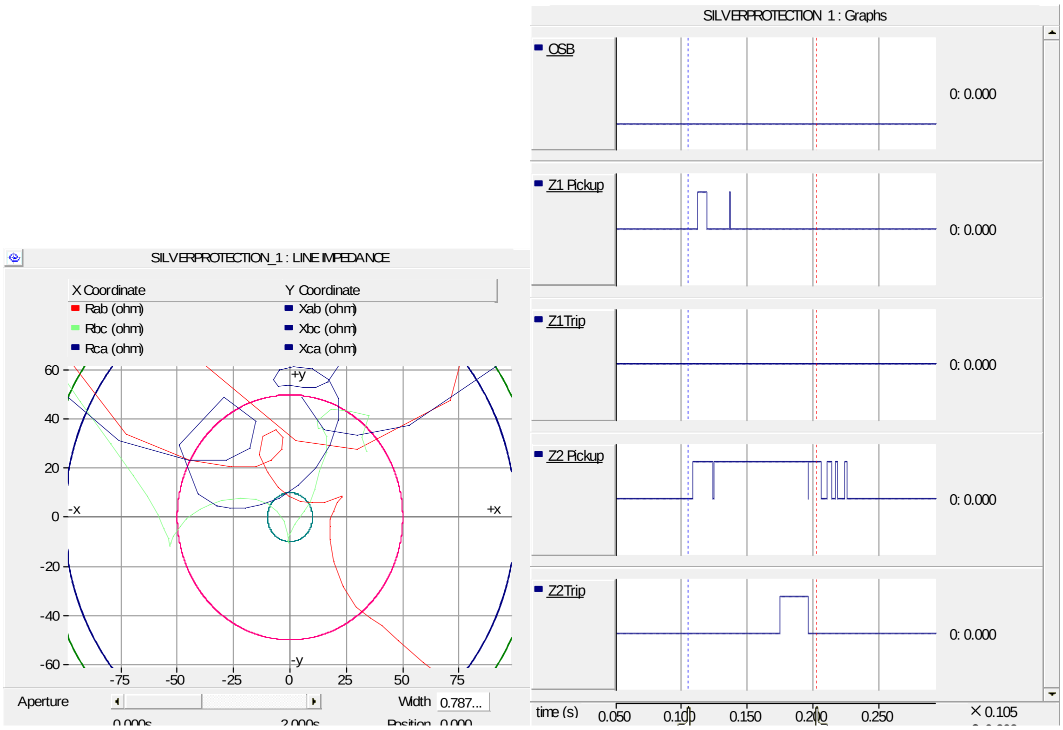
Manitoba Hydro electrical network is investigated to find Ferroresonant states in case of plant outage. Many states, which lead in Ferroresonance, are obtained for instance, energizing the network by one power source like Vermillion station, whereas other sources are out of service. Magnitude of voltage and current is increased in HV side of transformer in Silver station as shown in Fig. 7a. Phase plan diagram shows almost the same status as previous Ferroresonance. Misshaped and irregular circles in each time division are the evidence of existing Ferroresonance with chaotic mode (Fig. 7b). Hence, this kind of Ferroresonance is generally considered as chaotic mode.



(a) (b)

Fig. 7. Ferroresonance in case of plant outage. (a) Voltage and current waveforms, (b) phase plan diagram.

Fundamental value of voltage and current are changed so impedance locus enters the protective zones 1 and 2; hence, results in overreaching of distance relay. As shown in Fig. 7a, current is increased more than 2.8 kA_{pick} then is suppressed gradually. As it is shown in Fig. 8a, Zbc (green locus) enters the zone 1 of the relay for the time of about 0.08 s; hence, it causes relay picks up and then drops off immediately. All three phases pass through zone 2 so that trip condition is fulfilled due to remaining Zab (red locus) in the characteristic more than trip time value.



(a) (b)

Fig. 8. Distance relay in Ferroresonance in case of plant outage. (a) Impedance loci, (b) Operation of relay.

V. APPLICATION OF FERRORESONANCE DETECTION ALGORITHM IN DISTANCE RELAY

As it was shown in previous section, phase plan diagram is not able to recognize exact discrimination among Ferroresonance modes. Hence, a special tool is required to distinguish Ferroresonance of different types.

As it was discussed in advance, analysis of Ferroresonance in time domain represents a solution to detect Ferroresonance and determine Ferroresonance modes. It is used in distance relay to specify operation of relay in such conditions. Furthermore, the algorithm is able to search stability domain boundaries in Ferroresonance. In this section, a tool to detect and determine Ferroresonance modes is designed in distance relay by means of PSCAD/EMTC software and then relay is re-examined in above-mentioned Ferroresonant states; in addition, stability domain boundary of source voltages is specified in the network.

A. Ferroresonance detection tool in distance relay

Ferroresonance of different types are classified in four modes according to criteria in table I. A logical circuit based on THD and Fr.d measurement uses the criteria to detect Ferroresonance. As it is shown in Fig. 9, detection tool comprises measuring, comparator, logical gates, derivation, and time delay compartments.

In order to determine Ferroresonance mode, the values of THD and Fr.d are measured. Maximum value of THD is used for comparison. THD is selected after a delay of 0.05 s to eliminate interferences at the beginning of energizing. If the value of THD exceeds 50% and frequency remains at nominal value (Fr.d<1) fundamental mode of Ferroresonance is detected. Harmonic mode of Ferroresonance is detected when THD exceeds 50%, Fr.d exceeds 1 Hz and $\frac{\mathrm{dFr.d}}{\mathrm{dt}}$ is below 5 Hz/s. $\frac{\mathrm{dFr.d}}{\mathrm{dt}}$is calculated to determine periodic or non-periodic waveform. Increasing the value of $\frac{\mathrm{dFr.d}}{\mathrm{dt}}$is the evidence of existing non-periodic waveform. If the value of THD exceeds 100%, Fr.d exceeds 1 and $\frac{\mathrm{dFr.d}}{\mathrm{dt}}$ is more than 5 Hz/s quasi or chaotic mode of Ferroresonance is detected. The main difference between quasi-periodic and chaotic mode is almost qualitative. It depends on discontinuous or continuous harmonic spectrum; hence, detection algorithm considers them in the same mode. In this study, distance relay considers status of Ferroresonance detection tool to shift operating characteristics by selecting radius and center of the mho circles according to measured values of impedance to prevent operation of OSB and protective zones of the relay in Ferroresonance.

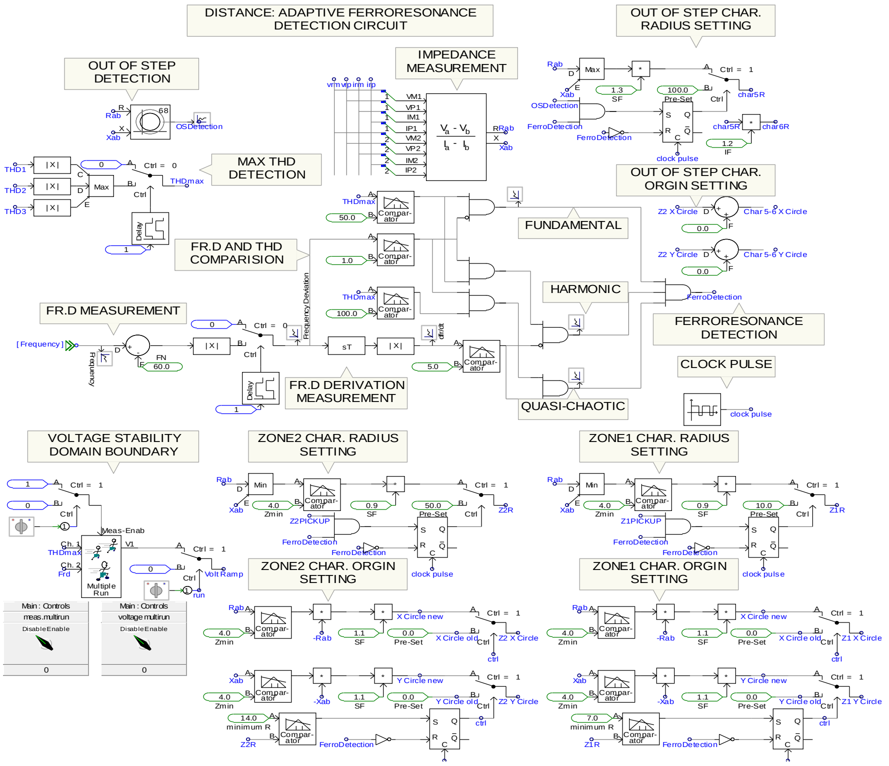
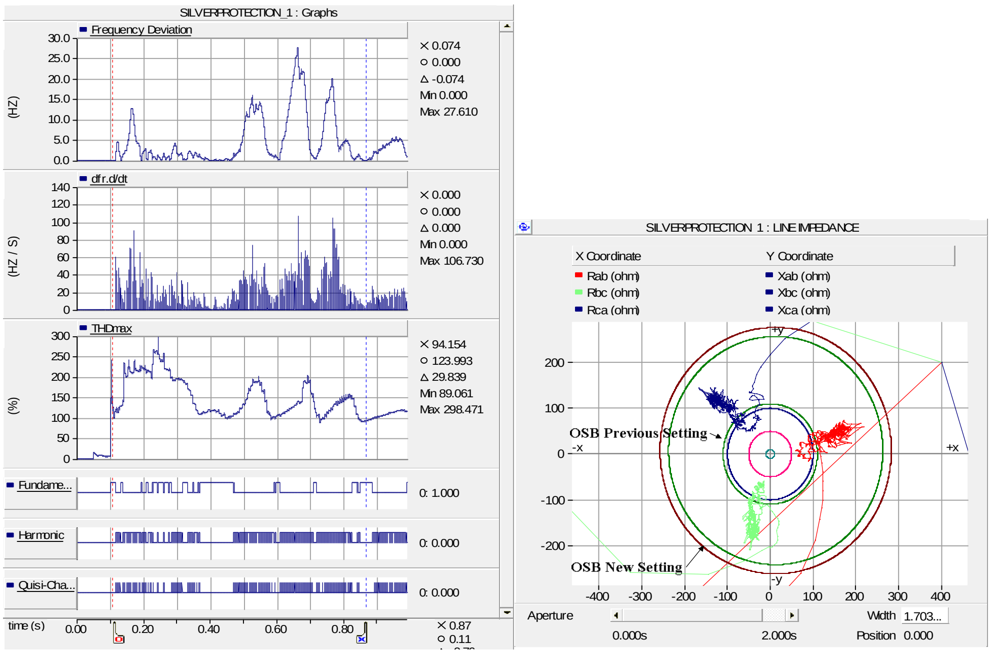


Fig. 9. Ferroresonance detection tool in PSCAD/EMTDC.

1) *Examination of Ferroresonance detection tool in Ferroresonance in case of changing line arrangement*

Ferroresonance in case of changing line arrangement was analyzed. In addition to misshaped waveforms, power oscillated in effect of frequency difference in the network. In this section, Ferroresonance detection tool determines modes of Ferroresonance. In this type of Ferroresonance, the value of THD oscillates. It is reduced close to of about 100%. Determination of Ferroresonance mode between harmonic and quasi-periodic or chaotic modes depends on the value of $\frac{dFr.d}{dt}$. Harmonic mode is emerged when this value is suppressed to zero, otherwise quasi-periodic or chaotic mode is emerged as present Ferroresonance mode. As it is shown in frequency deviation diagram (Fig. 10a), several points are detected with zero value in simulation time where the value of THD is more than 50% hence, fundamental mode is detected temporarily.

As it is shown in impedance diagram (Fig. 10b), impedance locus traverses in a limited area across OSB element. OSB setting modification of algorithm shifts the characteristics so that impedance oscillation in Ferroresonance does not traverse across the elements. Hence, in case of recognition of both out of step and Ferroresonance conditions, detection tool sets a flip flap to select between maximum value of R and X and then multiplies it to a security factor of 1.3 to keep stability margin. Resultant value is the radius of inner element. Radius of outer element is a factor of inner element in all conditions so that a value of 1.2 is chosen.



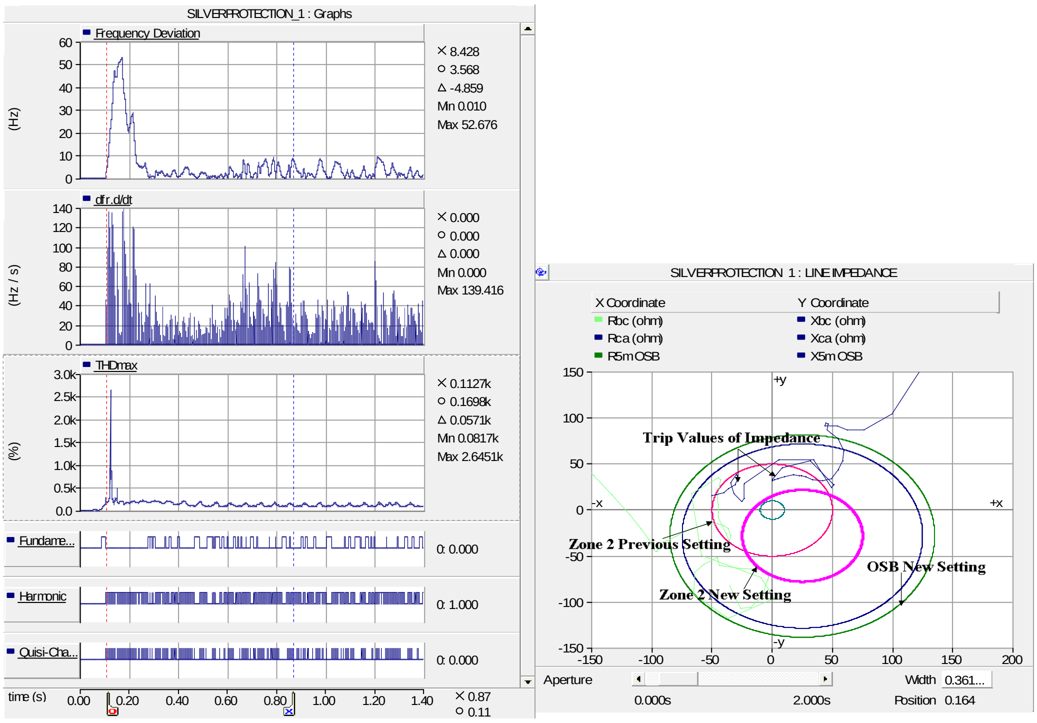
(a) (b)

Fig. 10. Detection tool in Ferroresonance in case of changing line arrangement. (a) Ferroresonance detection tool parameters, (b) OSB setting modification on impedance diagram.

2) *Examination of Ferroresonance detection tool in Ferroresonance in case of plant outage*

As it was shown in advance, plant outage emerges a Ferroresonance, which causes impedance loci enter the protective zones of distance relay and results in pickup and trip operation of zone 1 and 2 respectively. Ferroresonance modes are detected as well as previous state. As it is shown in Fig. 11a, frequency deviation gets zero value in several points and the value of THD is always more than 100%; hence, fundamental mode is detected several times in simulation. Determination of Ferroresonance mode between harmonic and quasi-periodic or chaotic modes depends on the value of $\frac{dFr.d}{dt}$. When this value is suppressed to zero, harmonic mode is emerged. Quasi-periodic or chaotic modes are emerged when $\frac{dFr.d}{dt}$ and THD are more than 5 Hz/s and 100% respectively.

Adaptive Ferroresonance detection tool is used to prevent operation of protective zones in this condition. As it is shown in Fig. 11b, Zca (blue locus) causes operation of zone 2 in Ferroresonance; hence, zone 2 is shifted as described beforehand by a security factor of 1.1 to keep stability margin. Therefore, trip values of impedances (pointed out in diagram), are located out of the element. In addition, OSB elements follows center of zone 2.



(a) (b)

Fig. 11. Detection tool in Ferroresonance in case of plant outage. (a) Ferroresonance detection tool parameters, (b) protective zone setting modification on impedance diagram.

3) Determination of stability domain boundary of source voltage in the network

Generally, stability domain boundary is determined based on source voltage versus capacitance. In this section, we decided to determine stability domain boundary of source voltages in Manitoba Hydro network. As it was mentioned in advance, Ferroresonance detection algorithm is able to determine stability domain boundary of parameters versus variation of THD and Fr.d. To do so, all source voltages are increased from zero to the values, which Ferroresonance is detected in one of Ferroresonant configurations (changing line arrangement), which has been investigated beforehand. It is performed by multiple run device to find the value of voltage in which cause Ferroresonance of different types. As it is shown in Fig. 12, source voltage versus THD and Fr.d is plotted in a 3 dimensional diagram to illustrate stability domain boundary. The specified green line in source voltage value shows no Ferroresonance area. Fundamental Ferroresonance mode is emerged in a source voltage of about 150 kV where the value of THD increases and Fr.d is almost zero. In addition to increasing THD, the value of Fr.d increases in the area specified with non-fundamental (harmonic-quasi-periodic or chaotic) Ferroresonance.

By means of this characteristic, protective system is able to predict Ferroresonance based on source voltage in a specific network arrangement. Pre-analysis of some operational arrangements assists the operator to keep away from magnitude of voltage or arrangement, which lead in Ferroresonance.

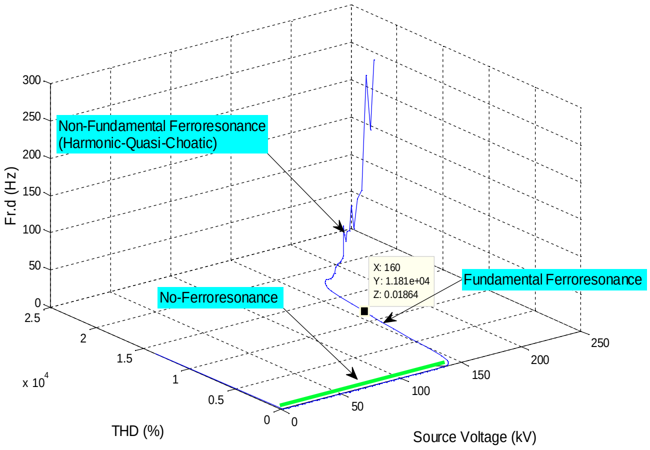


Fig. 12. Determination of stability domain boundary of network voltage.

VI. CONCLUSION

Distance relay with OSB element is in risk of false operation due to Ferroresonant states in the network. Power oscillation in Ferroresonance causes operation of OSB element and blocks the relay. Furthermore, increasing the magnitudes of parameters in Ferroresonance causes over reaching of the relay. Analysis of Ferroresonance in time domain by taking suitable criteria in to consideration makes a solution to determine Ferroresonance modes and stability domain boundaries in Ferroresonant configurations. Distance relay is equipped with a Ferroresonance detection tool, which determine Ferroresonance modes to change the operating characteristics and setting values. It results in prevention of false operation of the relay in Ferroresonance, whereas any fault does not occur in the system. Stability domain boundary based on source voltage is determined in electrical network. Hence, it is beneficial to use Ferroresonance analysis tools in distance relay to warn risk of Ferroresonance; furthermore, enable the relay to make a decision in Ferroresonant conditions according to protection strategy.

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BIOGRAPHY

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