Self-Adaptive Generator Protection Methods

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1. Introduction

The setting of many of the functions that are used to protect synchronous generators is relatively straightforward, requiring system or machine data that is readily available to the protection engineer. However, there are occasions where the effective application of a protection function requires detailed measurement and analysis of operational data from the machine. This paper identifies two such functions: Split Phase Protection and 3rd Harmonic Neutral Undervoltage Protection and discuss the particular application issues associated with each. These functions are responsible for detection of two of the most common types of stator winding failures; inter-turn faults and ground faults. A new algorithm is presented that can respond to the influencing system conditions and automatically adapt these functions accordingly. The resulting protection schemes are more sensitive, less likely to mis-operate, and are easier to set than their conventional counterparts.

2. Interturn Faults

A hydroelectric generator is often wound with a double-layer, multi-turn winding. The winding may be a single circuit or there may be two, four, six or eight branches in parallel. Under normal operation there is very little difference in the current in each branch. However, during an internal fault, currents will circulate between the parallel branches of the winding within one phase. Split phase protection takes advantage of this characteristic by measuring the current unbalance between these parallel branches. In hydro machines a significant percentage of stator faults begin as turn-to-turn faults 0. Due to the very high effective turns-ratio between the windings and the shorted turn, inter-turn faults cause extremely high currents in the faulted loop leading to quickly progressing damage.

These faults are not detectable by the stator differential or ground fault protections since there is no difference between the currents at the output and the neutral terminals and there is no path for fault current to ground. If these faults can be detected before they evolve in to phase or ground faults then the damage to the machine and associated downtime can be greatly reduced. Therefore the split phase protection should ideally be sensitive enough to operate for a single-turn fault in the winding of the machine.

2.1 Detection Methods

There are several methods currently in use today.

Scheme A

In scheme A, a neutral point is brought out for each parallel circuit. An overcurrent element is connected between each neutral. During an inter-turn fault, a circulating current is produced in the faulted phase that is passed between the neutrals.
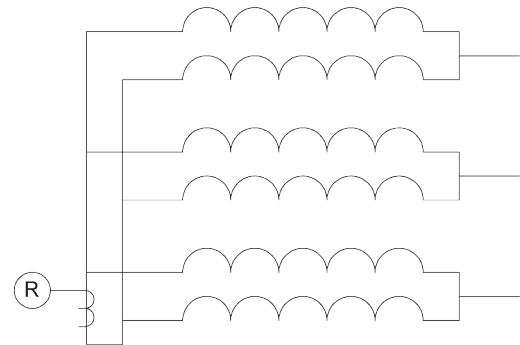

Fig 1.
Scheme A.

Scheme B

In this scheme a differential and restraint signal are derived using currents from both sides of the machine. One current represents the total current in the machine while the other is the current from a CT representing 1/2 the total current. This scheme is also known as "combined split phase and differential" or "partial longitudinal differential".
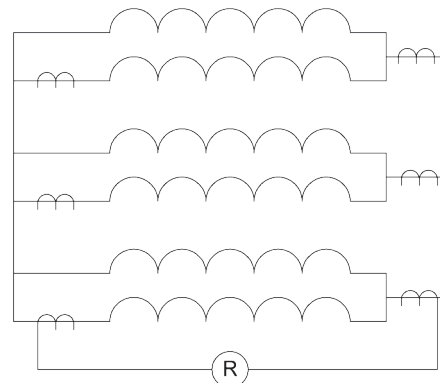

Fig 2.
Scheme B.

Scheme C

In scheme C, the currents from each parallel circuit are used to derive a differential and restraint signal. The relay has a percent slope characteristic. The restraint signal provides security against a false differential produced during an external fault while still allowing fast operation during internal faults. This scheme is sometimes known as "transverse differential".

Scheme D

The scheme shown in Figure 4 also responds to the difference between the currents in the two circuits. However, the summation is done outside the relay.
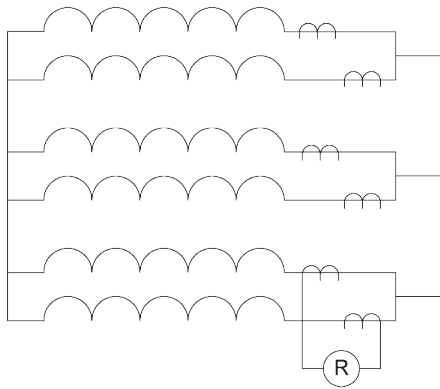
Fig 3.
Scheme C.

Therefore this method cannot derive a restraint signal. An instantaneous element using this signal must be set high enough to avoid pickup during an external fault. This will make the element relatively ineffective for detection of single-turn faults. As such this scheme usually employs a definite time or inverse time characteristic for security.
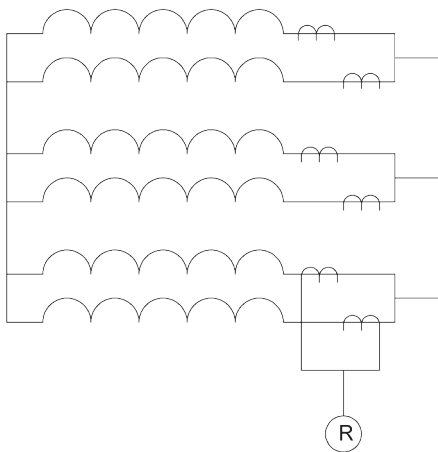

Fig 4.
Scheme D.

Scheme E

In this scheme a window-type CT is used to measure the difference between the current in each circuit, as shown in Figure 5. This method avoids the CT error issues of Scheme D.
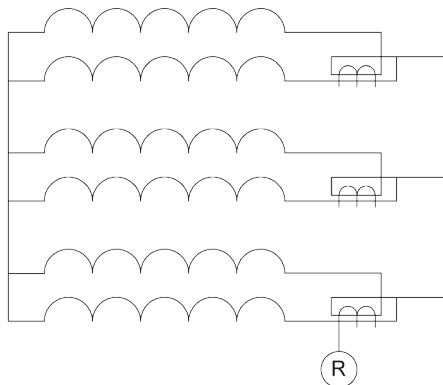

Fig 5.
Scheme E.

2.2 Characterization

Under normal operation the level of the inherent split phase current is usually less then 0.5% of the rated machine current 0. During an external fault many machines produce a transient circulating current. The magnitude of this transient can be several times larger than the steady state current and may persist for upwards of 30 cycles 0. For an internal fault, the magnitude of the circulating current corresponding to a single-turn short is dependent on several factors. These include the type of the winding (adjacent versus alternate pole) and the number of poles.

2.3 Application

A simple calculation can be carried out to approximate the circulating current due to a shorted turn as shown in the example system of Figure 6.
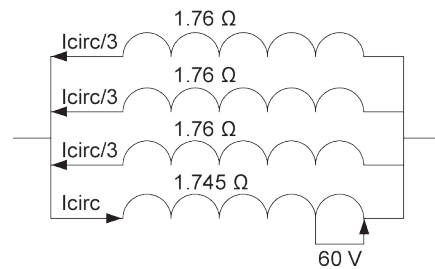

Fig 6.
Interturn Fault.

The machine in this example is rated at 65MVA and 13.8 kV. The stator winding has 4 parallel circuits, each made of 33 series coils and each coil having 4 turns. The rated current is 2700 amps. The winding impedance can be approximated by the leakage reactance (0.15 p.u in this case). Each healthy parallel branch will have 4 times the nominal impedance or 1.76 ohms. The impedance of a single turn is 0.013 ohms. The voltage across a single turn is 60 volts.

$$V_{turn} = \frac{V_{nominal}}{\sqrt{3} \quad N_{turns} \quad N_{coils}} = 60$$

$$I_{circ} = \frac{V_{turn}}{Z_{circuit} \quad Z_{turn} + \frac{Z_{circuit}}{N_{circuit} \quad 1}} = 26$$

This corresponds to a circulating current of about 1% of rated current.

2.4 Bypassed Coil

A failure in the winding of a machine requires its immediate removal from service until repairs have been carried out. Often the machine may be supplying critical load to the system. In this instance it is possible to carry out temporary repairs to the machine and place it back in service. These repairs typically entail isolating and bypassing the faulty coil. A machine operated under these conditions may be subject to overheating, magnetic pullover and excessive vibration requiring that it be

operated at a reduced load level. In the context of this paper, the bypassed coil can potentially have a dramatic impact on
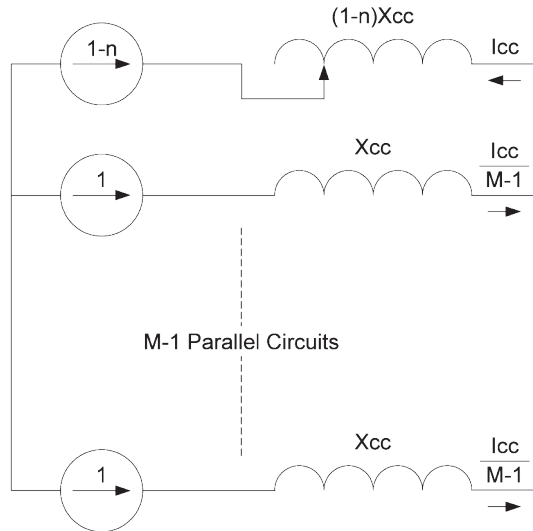

Fig 7.
Operation with a Bypassed Coil.

the inherent split phase current 0.

Figure 7 shows one phase of a machine with M parallel branches and a bypassed coil in one branch. The quantity X_{cc} can be approximated by the leakage reactance X_L 0.

The quantity n represents the number of coils bypassed expressed in per-unit. Inspection of the circuit illustrates the effect of a bypassed coil on the circulating current. It is evident that an interturn fault in a healthy branch (without a bypassed coil), can act to bring the circulating current back towards equilibrium; i.e. the fault may not necessarily translate into an increase in the split-phase current magnitude.

Figure 8 shows the split phase current in a model machine with a small portion of the stator winding bypassed in one phase. Power is displayed in per unit and split phase current in secondary amps. The bypassed winding creates a significant increase in the inherent split phase current. Additionally, the magnitude of
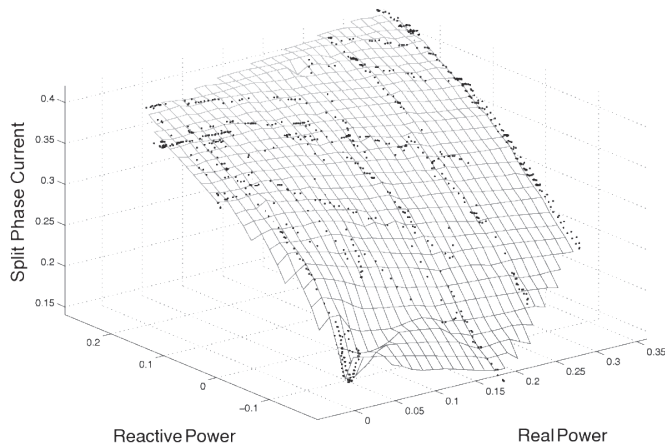

Fig 8.
Split Phase Current Measurements.

the split phase current displays a strong dependency on real and reactive power.

As a result the pickup setting of the split phase protection must

be increased to prevent false operation. This can make the function ineffective for the detection of single-turn faults.

3. Stator Ground Faults

Stator ground faults are short circuits between any of the stator windings and ground, via the iron core of the stator. Typically, when a single machine is connected to the power system through a step-up transformer, it is grounded through high impedance. As a result, the amount of the short circuit current during stator ground faults is driven by the amount of capacitive coupling in the machine and its step-up transformer. Therefore when a ground fault occurs, very small capacitive current flows making the short circuit difficult to detect.

Ground faults can be detected throughout most of the winding through the use of an overvoltage relay responding to the fundamental component of the voltage across the grounding impedance. The magnitude of this voltage is proportional to the location of the fault. Therefore, for faults at or near the neutral of the machine, this element is ineffective 0.

Little or no damage is done to the machine as a result of a ground fault close to the neutral. It does, however, prevent the overvoltage protection from detecting a second ground fault. If a second ground fault occurs, the grounding impedance does not limit the fault current. If the second ground is on the same phase it will not be detectable by the differential. The result can be potentially catastrophic damage to the machine 0. Therefore, a second method to detect faults close to the neutral and effectively prevent widespread damage to the machine is beneficial. This second method is sometimes known as 100% stator ground fault protection.
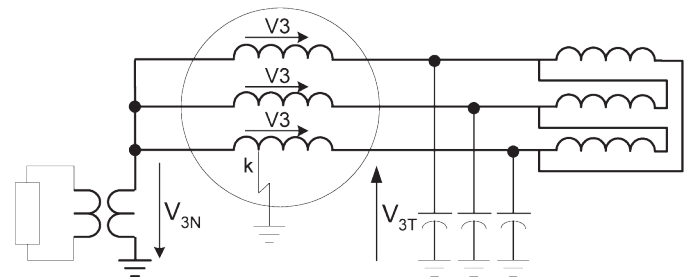

Fig 9.
Stator Ground Fault.

3.1 Detection Methods
Several techniques for 100% stator ground fault detection take advantage of the third harmonic voltage generated by the machine itself 0.

Under normal operating conditions a portion of the 3rd harmonic appears across the generator terminals and a portion appears across the grounding impedance as shown by the green line in Figure 10. For a fault at k, the distribution of the third shifts to the red line. This causes the third harmonic at the neutral to decrease and the third harmonic at the terminals to increase.

If the third harmonic can be measured both at the generator neutral and at the terminals, then a differential scheme can
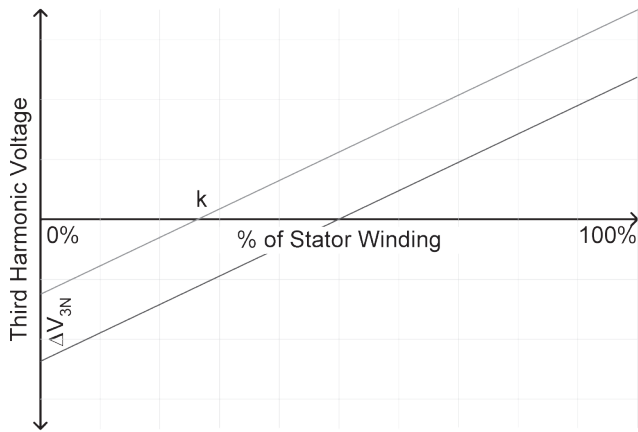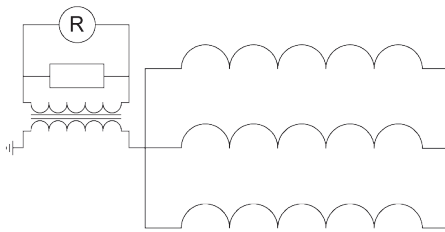
Fig 10.
Third Harmonic Distribution.

Fig 11.
Neutral Undervoltage Scheme.

be applied 0. This scheme is less sensitive to variations in the third harmonic due to machine loading. However, if the VT connection does not permit measurement of the third harmonic at the generator terminal end 0, comparison of the neutral and terminal end third harmonic signatures is impossible, then only the third harmonic neutral undervoltage element may be applied.

The third harmonic undervoltage element uses the voltage that forms across the high impedance ground, which is connected to the neutral point of the generator unless a better path to ground is presented. Figure 12 is an example of the third harmonic voltage measured at the neutral of a generator at various levels of real and reactive loading. Power is displayed in primary units and third harmonic voltage is displayed in secondary volts. During a ground fault close to the generator neutral the third
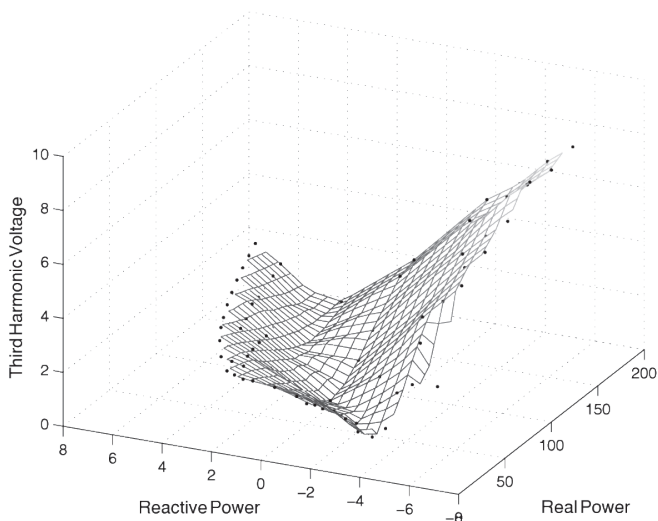
harmonic voltage will decrease or drop to zero.

In the scheme of Figure 11, a neutral voltage is measured from the machine neutral point. During a stator ground fault, the third harmonic will flow into the ground fault, shunting the neutral grounding path, and the measurement of neutral voltage will drop to or near zero.

3.2 Characterization

The characteristic of the third harmonic varies considerably between different machine designs; it can also vary considerably between machines of the same design due to manufacturing variation. Under normal operation the level of the third harmonic neutral voltage can vary considerably based upon machine output (MW), power factor (PF) and machine voltage (kV).

In order to provide optimum protection for the machine, the complete third harmonic characteristic must be found and the setting should be calculated based on this data. Data must be collected and then plotted with output (MW) along the X-axis and third harmonic neutral voltage (V) along the Y-axis as shown in Figure 13.

Once this data is plotted an appropriate tripping voltage should be determined. It should be significantly high such that the protection will function, even when the fault is further up on the winding. The setting must also allow enough margin to allow for variation and errors in the data collection and input accuracy.

A power blocking value should be derived so that it complements the tripping voltage. The local minimums in the third harmonic characteristic should be blocked allowing the highest possible tripping voltage.

There are several options for setting this function.

3.3 Type Testing

A simple method of setting this function utilizes the data from type tests for machines of the same design. Electrical machines of the same design and manufacture can be type tested and a standard set point can be calculated and used. This provides the easiest solution however it is the least effective and can provide less protection or lead to nuisance tripping.

3.4 Site Testing

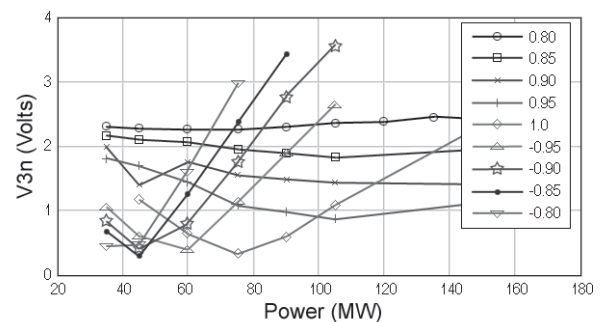The setting can be derived by taking site data for each machine

Fig 12.
Third Harmonic Voltage Characteristic.

Fig 13.
Third Harmonic Neutral Voltage Data.

by running the machine through the range of power output and power factor. Taking data at regular intervals will allow for a sufficiently accurate setting to allow for protection while keeping from false tripping. This method provides good protection but is more expensive than type tests and still allows the opportunity for data collection errors. An example of the data collected during a site test is shown in Figure 13.

3.5 Electronic Data Collection

If a data logger with sufficient memory exists in the applied protective relay 0, data logging can be used to collect operating data over the operating time. This data can be extracted from the data logger and used to calculate the setting. This method provides much more accurate characterization of the third harmonic, however the data may not cover the entire operating region. If the machine has not operated in those regions the protection setting decision may be made with incomplete data, which could lead to nuisance tripping or insufficient protection.

4. Self-Adaptive Protection Principles

The previous sections describe the deviation that can sometimes occur in the operating signals of the split phase and 3rd harmonic undervoltage element, as a result of active and reactive loading of the machine and the resulting problems relating to setting selection. It is proposed that for both functions a method could be derived to automatically adapt to these variables.

The method would measure and log the variations in the operating quantity over time in order to learn the characteristics under various loading conditions and operate based on a departure from this characteristic in order to protect the machine.

Implemented in a microprocessor-based device, data collection would entail sampling the voltages and currents and the operating quantities, filtering digitally, extracting magnitudes/ angles using a standard Fourier algorithm, and calculating active and reactive quantities from these.

The method would allow for the protection to become active as soon as the data has been collected. The function could be proactively enabled and disabled to protect for operating conditions where sufficient operation data has been collected and block for operating conditions where insufficient data has been collected.

The function would require a security margin to account for measurement errors.

A best-fit curve could be calculated to approximate the operating characteristic; there are several methods for forming this function. This method would require recalculation of the curve each time data is collected and would be very processor intensive.

Alternately, the operating characteristic could be approximated by an array of data points stored to create a mesh of operating signal values spaced equally over the active-reactive power region. This method requires more memory to store the data but is less processor-intensive.
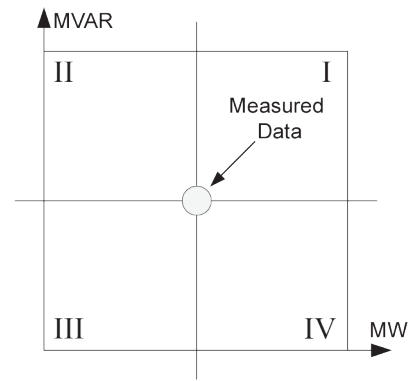

Fig 14.
Operating Data Array.

Data would be collected whenever the machine is in operation. The data would be used to update the array holding the operating data for the machine. Since the array consists of a finite number of elements, the measured value of the operating signal data would not usually correspond exactly to a point in the array (points 1-4 in Figure 14).

Therefore, either the point closest to the measured value could be updated or all four adjacent points could be updated simultaneously.

Before the data could be used for fault detection the data must be validated. This could be a manual operation – the data could be downloaded and analyzed. If satisfactory the function could then be placed in-service.

Alternately, the validation of the data could be automated. In such a scheme, a test could be carried out on the data to determine whether or not it is changing dramatically between successive samples. An additional test would be to examine the smoothness of the characteristic over successive data points.

An important consideration is the number of points in the array required for an accurate representation of the data. The factors influencing this determination include the smoothness of the operating characteristic, the method used to interpolate between points in the array and the accuracy required by the function.

Once the data has been validated it may be used for fault detection. Again, it is unlikely that the measured value of P and Q will correspond to a point in the array.

An expected operating value must therefore be calculated for each value of P and Q. Since this function is adaptive the value must be calculated in real time.

Terminal voltage can have a significant effect on the quiescent value of the operating signal. The signal can be similarly affected during other system disturbances. Therefore it is important to inhibit learning during these periods. This can be achieved by monitoring of the positive sequence voltage and current. Learning is inhibited if the positive sequence voltage is lower than its nominal range. Learning is also inhibited when the positive sequence current is greater than its nominal value. Additionally, some machines may exhibit a significant difference in the operating signal between the offline and online state. In such cases, learning may also be supervised by breaker position. Once system conditions return to normal for a definite

period, normal learning can resume. Similar supervision can be applied in the tripping mode.

5. Development of Adaptive Algorithms

As explained in the previous section adaptive algorithms in this application consist of two parts. First, a learning procedure is required to establish the operate/restraint surface based on the measured data over longer periods of time. Second, an operate logic is required to use the learned surface for tripping at a given time.

This section presents practical ways of implementing such algorithm. The equations are derived for two-dimensional situations, i.e. when a single operating quantity depends on two variables, but can be easily extended onto generalized multi-dimensional cases.

5.1 Learning Procedure

With reference to Figure 15, an operating quantity X under non-fault conditions in a function of two variables, P and Q. In our
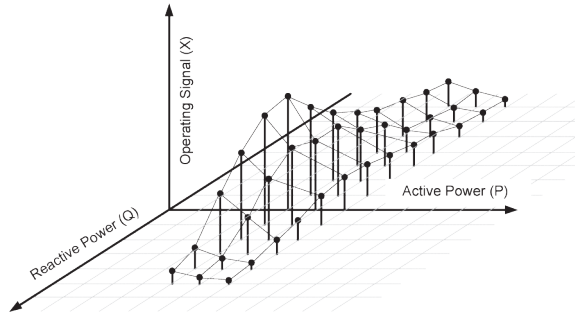

Fig 15.
Normal Operation Surface.

application P and Q are active and reactive power in the export direction, and X is the window CT current magnitude or angle in case of split-phase protection, and the third harmonic voltage magnitude in the case of stator ground fault protection.

The normal operation surface is represented by a finite amount of points in the form of a grid. Assuming the same grid size for the active and reactive power, Δ, the grid coordinates are:

$$P_i = \Delta \cdot i, \quad i = 0 \ldots N_{max} \qquad (1a)$$

$$Q_j = \Delta \cdot j, \quad j = -M_{max} \ldots M_{max} \qquad (1b)$$

Note that the active power is assumed positive, as there is no need to keep this method operational under the short periods of abnormal reverse-power operation of the machine. If needed, the implementation can easily be extended to cover all four quadrants of power.

During normal or abnormal operation of the machine, the measuring unit of the relay, returns the following operating point:

$$(X, P, Q) \qquad (2)$$

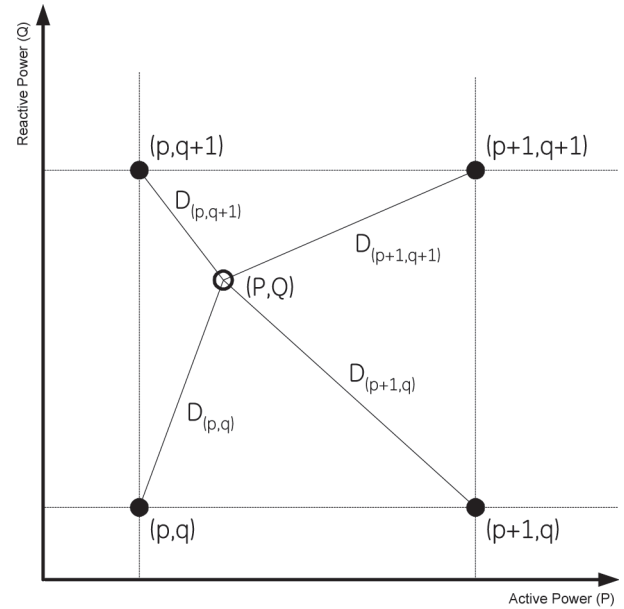First, this point must be related to the finite grid representing the operate/restraint surface:

Fig 16.
Calculation of Distances.

$$p = floor\left(\frac{P}{\Delta}\right) \qquad (3a)$$

$$q = floor\left(\frac{Q}{\Delta}\right) \qquad (3b)$$

Where floor stands for rounding down to the nearest integer.

The operating point is located between the following four corners of the grid (Figure 16):

$$(p,q)(p,q+1)(p+1,q+1)(p+1,q) \qquad (4)$$

During the learning phase, the value of X shall be used to adjust all four corners surrounding the operating point. Different approaches can be used.

In one method, all four points are treated equally and use the same value to adjust the value of the learned X. For example:

$$X_{(p,q)NEW} = (1-\alpha) \cdot X_{(p,q)OLD} + \alpha \cdot X \qquad (5a)$$

In the above, a smoothing filter is used for extra security. Only a small fraction of the measurement (α) is added to the previous value. In this way the sought value at the (p, q) point of the grid reaches its steady state asymptotically, and the value of α controls the speed of learning. The higher the α, the faster will be the convergence.

Similar equations are used to adjust the other three corners around the measuring point:

$$X_{(p,q+1)NEW} = (1-\alpha) \cdot X_{(p,q+1)OLD} + \alpha \cdot X \qquad (5b)$$

$$X_{(p+1,q+1)NEW} = (1-\alpha) \cdot X_{(p+1,q+1)OLD} + \alpha \cdot X \qquad (5c)$$

$$X_{(p+1,q)NEW} = (1-\alpha) \cdot X_{(p+1,q)OLD} + \alpha \cdot X \qquad (5d)$$

In another method, the closer the operating point to a given point of the grid, the higher the impact on the learned value for that point of the grid. This can be accomplished using the following equations for learning.

First, the relative distances between the operating point and the four corners are calculated:

$$D_{(p,q)} = \frac{(p \cdot \Delta - P)^2 + (q \cdot \Delta - Q)^2}{2 \cdot \Delta^2} \quad (6a)$$

$$D_{(p,q+1)} = \frac{(p \cdot \Delta - P)^2 + (q \cdot \Delta + \Delta - Q)^2}{2 \cdot \Delta^2} \quad (6b)$$

$$D_{(p+1,q+1)} = \frac{(p \cdot \Delta + \Delta - P)^2 + (q \cdot \Delta + \Delta - Q)^2}{2 \cdot \Delta^2} \quad (6c)$$

$$D_{(p+1,q)} = \frac{(p \cdot \Delta + \Delta - P)^2 + (q \cdot \Delta - Q)^2}{2 \cdot \Delta^2} \quad (6d)$$

These distances can be used to speed up the learning for corners located closer to the operating point:

$$X_{(p,q)NEW} = (1 - \alpha \cdot (1 - D_{(p,q)})) \cdot X_{(p,q)OLD} \\ + \alpha \cdot (1 - D_{(p,q)}) \cdot X \quad (7a)$$

$$X_{(p,q+1)NEW} = (1 - \alpha \cdot (1 - D_{(p,q+1)})) \cdot X_{(p,q+1)OLD} \\ + \alpha \cdot (1 - D_{(p,q+1)}) \cdot X \quad (7b)$$

$$X_{(p+1,q+1)NEW} = (1 - \alpha \cdot (1 - D_{(p+1,q+1)})) \cdot X_{(p+1,q+1)OLD)} \\ + \alpha \cdot (1 - D_{(p+1,q+1)}) \cdot X \quad (7c)$$

$$X_{(p+1,q)NEW} = (1 - \alpha \cdot (1 - D_{(p+1,q)})) \cdot X_{(p+1,q)OLD} \\ + \alpha \cdot (1 - D_{(p+1,q)}) \cdot X \quad (7d)$$

Version (7) has an advantage over version (5) when the operating point lingers at the border line between two different segments of the grid – it provides smooth transition between training one set of point versus a different set of points on the grid.

Equations (5) and (7) average the data when forming the operate/restraint surface by means of exponential convergence. A separate check must be designed to decide if a given value learned in the process is final and could be trusted, i.e. used by the operating logic.

Two criteria are used to decide if a given point is properly trained.

First, it is checked if the update process as dictated by equation (5) or (7) stops changing the value. This is determined by checking the increment after the update takes place. For example, when using form (7) one checks:

$$FLG_{1(p,q)} = \left| X_{(p,q)NEW} - X_{(p,q)OLD} \right| < \beta \cdot X_{(p,q)NEW} \quad (8)$$

Where β is an arbitrary value expressing the percentage difference that identifies the steady state is being reached.

The above flag is calculated each time a given point on the grid is updated as a part of the learning procedure that is for all four points surrounding the operating point.

Second, it is checked with the surface emerging in response to learning is smooth. This is determined by checking differences between the surrounding points on the grid:

$$FLG_{2(p,q)} = \left| X_{(p,q)} - X_{(p-1,q)} \right| < \delta \cdot X_{(p,q)} \quad \& \quad \dots$$

$$\dots \& \left| X_{(p,q)} - X_{(p+1,q)} \right| < \delta \cdot X_{(p,q)} \quad \& \quad \dots$$

$$\dots \& \left| X_{(p,q)} - X_{(p,q-1)} \right| < \delta \cdot X_{(p,q)} \quad \& \quad \dots$$

$$\dots \& \left| X_{(p,q)} - X_{(p,q+1)} \right| < \delta \cdot X_{(p,q)} \quad (9)$$

Where β is an arbitrary factor. Equation (9) takes exception for the points on the outer border of the grid – these points have only three, not four, neighboring points.

For a given point on the grid (p, q) to be considered trained, both the flags (8) and (9) must be asserted.

The learning procedure can be summarized as follows:

1. Take the measurement of the operating point (equation (2).
2. Calculate the coordinates of the grid (equation (3).
3. Update the four corners of the grid surrounding the operating point (equations (6) and (7).
4. Calculate the first validity flag for the four updated points (equation (8).
5. Calculate the second validity flag for the four updated points and their neighbors (equation (9).
6. Update the validity flags for the affected points on the grid.

6. Simulation Results

Figures 17-21, illustrate the learning procedure using an arbitrary surface. In this example the operating quantity is given by the following equation:

$$X = P \cdot e^{P^2 + Q^2} \quad (10)$$

For the third harmonic undervoltage function the following design constants are selected:

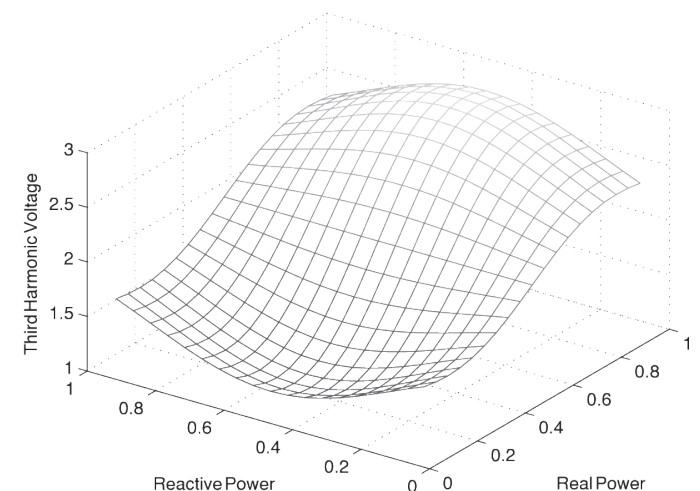$$\Delta = 0.05pu, \quad N_{max} = 25, \quad M_{max} = 25$$

Fig 17.
Simulated 3rd Harmonic Characteristic.

$\alpha = 0.05, \quad \beta = 0.03, \quad \delta = 0.03$

For the split phase function the following design constants are selected for both the current magnitude and angle:

$\Delta = 0.125pu, \quad N_{max} = 10, \quad M_{max} = 10$

$\alpha = 0.05, \quad \beta = 0.03, \quad \delta = 0.03$

The above means the (P, Q) grid stretches as follows (0,1.25pu) for the active, and the reactive power.

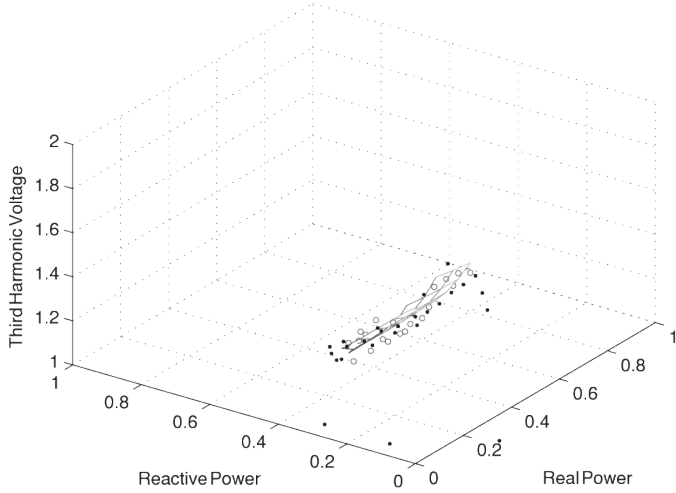Figure 17 presents function (10). This is the target function that should be learned by the procedure.

Fig 18.
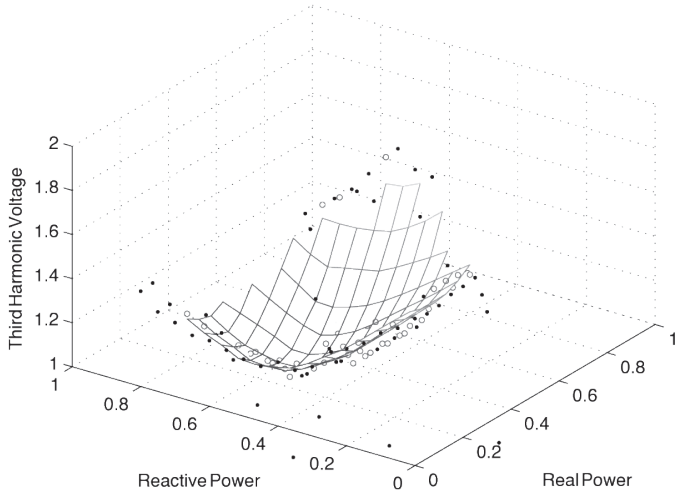*Learned Data at 1.7 Hr at 1 Sample/Sec.*

Fig 19.
Learned Data at 3.4 Hr at 1 Sample/Sec.

During the training, the operating point was varied randomly to wander within the assumed (P, Q) space. For each (P, Q) pair, the X value was calculated per equation (10), thus creating the measured operating point per equation (2). This operating point was injected into the learning algorithm.

Figures 18 and 19 present the shape of the operate/restraint surface at various stages of the learning.

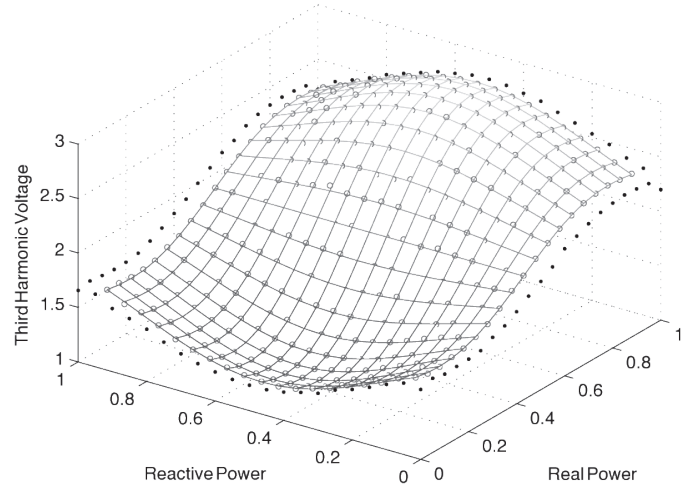These plots display the validity flags for the points on the grid.

Fig 20.
Final Learned Data.

• - "not learned" points of the surface.

o - "learned" points of the surface.

Figure 20 shows the final learned surface at the end of the process. This shape is identical with the assumed model of the process (10), proving the learning procedure is stable and capable of re-creating the process.

7. Tripping Logic

Before the learned surface can be used to detect sudden changes and be used for tripping, the validity of the learned points on the (P, Q) grid needs to be verified. With reference to Figure 16, a given measurement point is approximated by four surrounding corners on the grid. Operation (3) is executed as a part of the tripping logic to obtain the grid coordinates. All four corners (p, q), (p, q+1), (p+1,q+1), (p+1,q) must be valid in order to proceed.

When valid, the four corners are used to interpolate the expected value of the operating signal. A weighted average can be used for this approximation:

$$D = D_{(p,q)} + D_{(p,q+1)} + D_{(p+1,q+1)} + D_{(p+1,q)} \tag{11a}$$

$$X_{EXPECTED} = \frac{1}{D}\left(X_{(p,q)} \cdot D_{(p,q)} + X_{(p,q+1)} \cdot D_{(p,q+1)} + \ldots\right.$$
$$\left.\ldots + X_{(p+1,q+1)} \cdot D_{(p+1,q+1)} + X_{(p+1,q)} \cdot D_{(p+1,q)}\right) \tag{11b}$$

Where the four distances are calculated for a given value of X using equations (6).

The tripping logic checks for differences between the expected and actual values.

The third harmonic undervoltage function operates if:

$$V_{3N} < X_{EXPECTED} - \Omega \tag{12}$$

Where Ω is a security margin.

The split-phase protection operates if

$$\left|I_{SP} - |X1_{EXPECTED}|\angle X2_{EXPECTED}\right| > \Pi \tag{13}$$
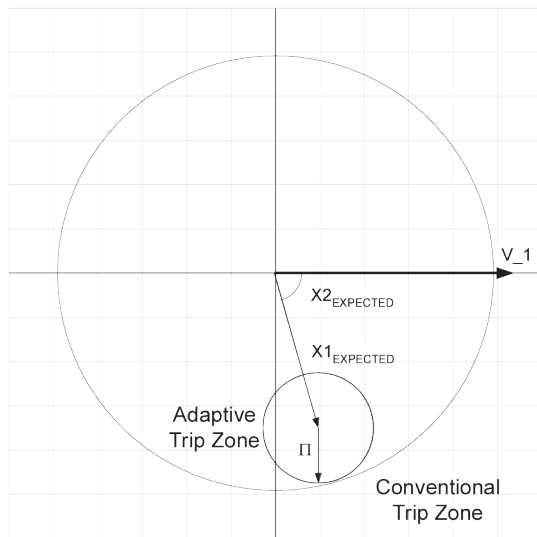
Fig 21.
Adaptive Split Phase Function.

Where Π is a security margin. The characteristic for the split phase function is illustrated in Figure 21.

In the above operating equations the security margins can be expressed as a fixed values, or as percentages of the expected value, or both in a combination.

Separate learning procedures are executed for the third harmonic undervoltage function, and for each phase of the split phase overcurrent function.

In a practical device it will be necessary to export and import learned data if, for instance the protective device is replaced. Also it will be necessary to signal to the algorithm that a repair has been carried out and it is necessary to re-evaluate the learned data.

8. Conclusion

In the area of generator protection the current state of microprocessor-based technology presents opportunities to overcome the limitations of conventional protection schemes. This paper has focused on two candidates: split phase protection and third harmonic undervoltage. It has been shown that these

functions can present challenges for effective application. It has also been demonstrated that adaptive algorithms can be designed to circumvent these problems and can result in a function that is more sensitive over a wider range of operation.

Moving forward the authors intend to prototype the algorithms in a microprocessor-based device and carry out field trials on in-service machines in order to validate the methods, optimize the design constants used in the algorithm, and identify possible opportunities for improvement.

9. References

[1] H.R. Sills, J.L. McKeever, "Characteristics of split phase currents as a source of generator protection," *AIEE Trans.* vol. 72, pp. 1005-1016, 1953

[2] J. DeHaan "Electrical Unbalance Assessment of a Hydroelectric Generator with Bypassed Stator Coils," *International Conference on Electric Machines and Drives*, pp. 803-805, May 1999

[3] R.G Rhudy, H.D. Snively, J.C. White, "Performance of Synchronous Machines Operating with Unbalanced Armature Windings" *IEEE*

   Transactions on Energy Conversion, vol. 3, no. 2, June 1988

[4] J.W. Pope, "A Comparison of 100% Stator Ground Fault Protection Schemes for Generator Stator Windings" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, no. 4, April 1984

[5] IEEE Guide for Generator Ground Protection, IEEE Standard C37.101, 1993

[6] IEEE Guide for AC Generator Protection, IEEE Standard C37.102, 1995

[7] "G60 – Generator Management Relay. Instruction Manual", General Electric Publication No. GEK-106228B, 2001

[8] Ouyang Bei, Wang Xiangheng, Sun Yuguang, Wang Weijian, Wang Weihong, "Research on the Internal Faults of the Salient-pole Synchronous Machine," Power Electronics and Motion Control Conference, pp. 558-563, Aug. 2000

[9] V. A. Kinitsky, "Calculation of internal fault currents in synchronous machines," IEEE Trans. Pattern Appl. Syst., vol. PAS-84, no. 5, pp. 391–389, May 1965

[10] D. Finney, G. Brunello, A. LaCroix, "Split Phase Protection of Hydrogenerators" Western Protective Relay Conference, Oct. 2005