IMPROVING OVERCURRENT RELAY RESPONSE TIME MODELS TO ACCOUNT FOR HARMONIC DISTORTIONS OF ELECTRICAL TRANSIENTS IN POWER SYSTEMS

Roy Vincent L. CANSECO and Rowaldo R. DEL MUNDO

University of the Philippines, Quezon City, Philippines

Abstract : This paper presents a means of improving relay time response predictions by taking into account the effects of harmonic distortions found in power system transients. A methodology of statistical nature using overcurrent relay modeling techniques such as direct data storage, curve-fitting, and parameter estimation is proposed. Regression models were developed to model the characteristics of overcurrent protective relays in the presence of harmonic distortion. The models created were verified through comparison with manufacturer's curves and empirical data from previous research. The results were represented in waterfall plots. An example of the usage of the models in improving relay response time prediction to overcurrents in power system transients is presented.

Key words : Overcurrent Protection Relay, Power Systems

INTRODUCTION

Protection relays detect faults in the power system and issue tripping signals to isolate compromised portions of the network. The first generation relays are electromechanical, the second generation are solid state. The third and latest generation is microprocessor-based. Protection relays are mainly classified into overcurrent relays, distance relays, and differential relays. The most common of these are overcurrent relays. They are being used as primary and backup protective devices and can be found in every type of power system protection zone. It is the primary protection for distribution feeders. It is also used as backup protection for transmission lines against phase or ground faults [1].

Manufacturers give overcurrent relay data in the form of time current characteristic curves (TCC). These come from the relay design that assumes a phasor input such as 60 Hz. These cannot predict relay operation in the case of evolving currents and in the presence harmonics or off-nominal frequency currents.

Many of the current modeling methodologies are based on relay construction and operation [2] [3]. Modeling may also be based on the results of relay characterization, wherein a set of inputs is fed to the relay and the outputs are recorded and analyzed in order to develop mathematical models that fit the data. The advantages are many. Characterization-based methodologies do not differentiate between relay generations [4]. The process does not require detailed relay construction information. The results are approximate but accurate for the range where there is sufficient data, that is, the range characterized.

RESEACH METHODOLOGY

Time intervals between coordination curves are required because the simplified, single-characteristic curves of overcurrent relays do not include allowances for manufacturing tolerances, relay overtravel, nonideal instrument transformer performance, breaker operating time, and other hard-to-define variables. Some of these hard-to-define variables may be derived from the design of the equipment, however, it is considered impractical to do so. Another reason is that manufacturers will never disclose their designs in entirety.

For more accurate simulations, generic relay models can be modified to take into account statistically derived relay transient characteristics. To improve the investigating of relay mal-operation, effects of deviations of electrical transients from the ideal current waveform must be studied.

Fig. 1 shows the methodology used in the study. It starts with obtaining data from the transient-based relay testing. It follows by determining equations that describe the operating time of the relay by a parameter of interest such as current magnitude. This is followed by interpolation to weave the equations together with respect to a related parameter of interest such as current waveform frequency. This allows the modeling of the relay transient characteristic operating time in terms of two related parameters such as frequency and current magnitude or amount distortion and distorting harmonic number. Such representation lends insight to the transient characteristics of the relay.

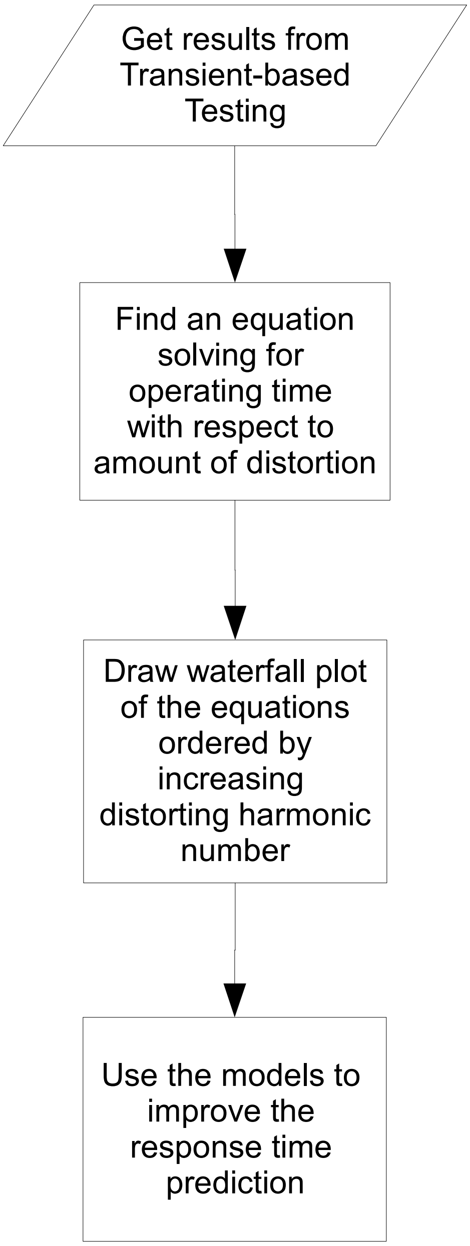

Fig. 1: Methodology

RESULTS AND DISCUSSION

Transient modeling based on relay characterization begins with recreating the transient input signals as well as the plotting the performance of the relay against the input given. The mathematical model is then developed to achieve close agreement with the empirical data for each of the relays characterized. The list of relays are in the appendix.

3.1 Single Harmonic Distortion Models

The fundamental and harmonic pair inputs take the form A*sin(2*pi*f*t)+k*A*sin(2*pi*n*f*t) , where A is the amplitude of the input, k is a factor to determine the amplitude of the distorting harmonic relative to the fundamental, f is the frequency of the fundamental, and n is the integral harmonic number. The time in seconds is designated as t. The inputs are programmed into MATLAB with a time step of (0.01/f) for smooth plotting. An example of the input is shown in Fig. 2. The amplitude of the fundamental is of unit height and the amplitude of the distorting second harmonic is half that.

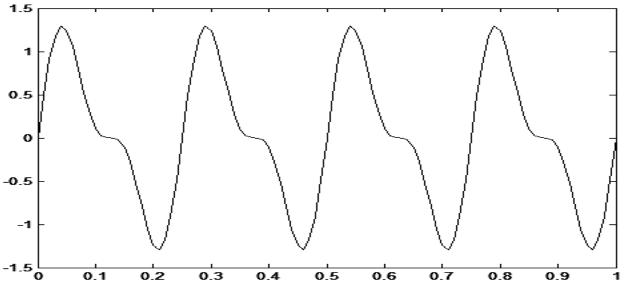

Fig. 2: Phasor and harmonic pair input

The models were created to describe the operating time with respect to the distorting harmonic as well as the amplitude of the harmonic relative to the fundamental. Distortion of the input waveform can cause variations in relay operation. However, practical relays have minimum operating times as determined by their construction. The curve fitted is exponential in nature in order to assure that the model decays to a minimum time value either when there is no distortion or when there is infinite distortion, depending on the relay type. This is because data in literature shows electromechanical relays, in general, speed its operation as distortion is added while microprocessor-based relays slow down with distortion [3]. The equations of the models were generated with through regression analysis with an exponential function of the form of Eq. (1). Since the minimum operating time value is greater than zero, a constant term must be added (a0). A scaling constant (a1) allows the model to adapt to the scale of the x-axis, which is the percent of the distorting harmonic. The constant b determines amount of curving or the shape of the exponential function.

$$t_{trip}(x)=a_0+a_1e^{bx} \qquad (1)$$

The constant a0 is the physical minimum time needed for the relay to operate. The constant a1 is the scaling factor. From literature, it was determined that the curve of the exponential function has a b of approximately +-0.032114 [5].

Previous research took values at 3% harmonic distortion and 50% harmonic distortion. To improve the model, another point was determined at 0% harmonic distortion. Every relay was tested using the second to the tenth harmonic. This give nine 3%, 50% pairs from which a value for the 0% distortion was extrapolated. Since being just one relay, it must have only one value for 0% distortion, the extrapolated results were averaged to come up with a single value.

Data fitting is done to solve the values of a0, a1, and the sign for b. The software EzyFit was used to do this. Ezyfit is a free third-party software add on to MATLAB. A description of Ezyfit can be found in the appendix.

RELAY RESPONSE TIME MODELING

For 10th harmonic distortion, the operation of the CO-9H relay is modeled as shown in Fig. 3 for varying amounts of distortion. The value of the constants for the mathematical model are also shown. R describes the fit. A good fit would have an R value close to 1.

The transient-based testing data provided the relay operating time for 50% distortion and 3% distortion. In order to create time response characteristic equations, three or more data points are preferred. A third point can be found simply looking for the operating time without distortion, or equivalently, the operating time with 0% distortion. This point must be the same for all the distortion data irregardless of the harmonic number of the distorting harmonic. For the purpose of this study, linear extrapolation was done to approximate the operating time at zero distortion. This was done for the 2nd to the 10th harmonic data. Since the value for the zero distortion operating time should be the same irregardless of the harmonic number, the nine estimated values were averaged. This gives the third data point.

A figure similar to Fig. 3 will result if the points corresponding to the operating time of the CO9H relay with 10th harmonic distortion was plotted.

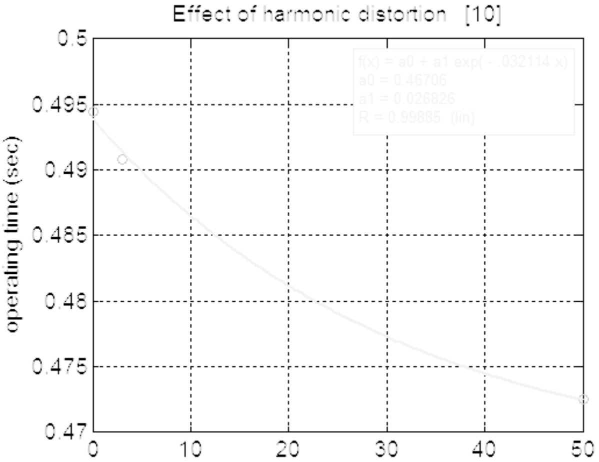

Fig. 3: 10th harmonic distortion effect for the CO-9H relay

The RMS error was computed for the model in Fig. 3 to be 5.6591 milliseconds, which is around a third of a cycle. The RMSE was computed by first obtaining the absolute value difference of the three points with the corresponding model predictions. The mean of the squares of these differences are taken. The RMSE is the square root of computed mean.

An equation was developed for each of the harmonics characterized for the CO-9H relay. Table 1 gives the values for the constants to describe the operation for the harmonics characterized for the CO-9H relay as well as the corresponding error estimates. The same was done for the G.E. 12IFC53A1A electromechanical relay in Table 2.

Table 1: Model coefficients for the CO-9H relay

harmonic	2	3	4	5	6	7	8	9	10
a0	0.360110	0.360110	0.434480	0.474610	0.471760	0.478840	0.491580	0.476300	0.467060
a1	0.140620	0.140620	0.062931	0.019135	0.022063	0.013525	0.002947	0.018828	0.026826
b	-0.032114	-0.032114	-0.032114	0.032114	0.032114	0.032114	0.032114	-0.032114	-0.032114
RMSE	5.1155E-03	5.2538E-03	2.4001E-03	4.8368E-04	4.6342E-04	1.4589E-03	1.2374E-04	5.4829E-04	5.6591E-03

Table 2: Model coefficients for the IFC53 relay

harmonic	2	3	4	5	6	7	8	9	10
a0	0.479220	0.454520	0.457140	0.439580	0.426970	0.377660	0.289190	0.330660	0.366320
a1	0.232160	0.259090	0.256200	0.272550	0.285700	0.338480	0.431700	0.386380	0.348500
b	-0.032114	-0.032114	-0.032114	-0.032114	-0.032114	-0.032114	-0.032114	-0.032114	-0.032114
RMSE	6.3490E-02	1.4771E-02	4.3422E-03	3.2563E-03	3.7278E-03	6.4885E-03	1.0362E-02	7.2002E-03	2.0213E-02

The same procedure was implemented on the rest of the relays under study.

When the models for the effects of single harmonic distortion for a single relay are placed along side each other in a waterfall plot, the result reveals the amount of distortion necessary to alter relay operation. For an electromechanical relay as in Fig. 4, it takes around 10% single harmonic distortion to affect the operating time of the relay. Electromechanical relays have adjacent harmonics affecting the operating time in like manner. For the CO-9, the 2nd to 4th harmonic tend to lower the operating time, while the 5th to 7th harmonic increase it. Distortions of the 8th to 10th harmonic do not affect relay response for the range of up to 50% of the magnitude of the fundamental. The model shows that single harmonic distortions in electromechanical relays introduce operating time variations of within an average of 0.25 seconds for the relays characterized.

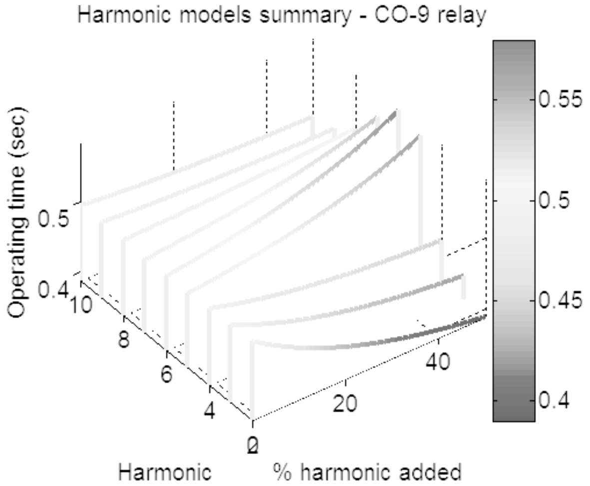

Fig. 4: Operating time with distortion for the CO-9H relay

A waterfall plot of response time with respect to the amount and type of harmonic distortion was made for each of the protection relays studied.

3.2 Application to a Field Recorded Transient

A recorded transient waveform from the feeder inrush in a local utility serves as the multi-frequency transient input. It is shown in Fig. 22. The data from the graph of the waveform was extracted using the open-source g3data software. A brief explanation of the software is in the appendix.

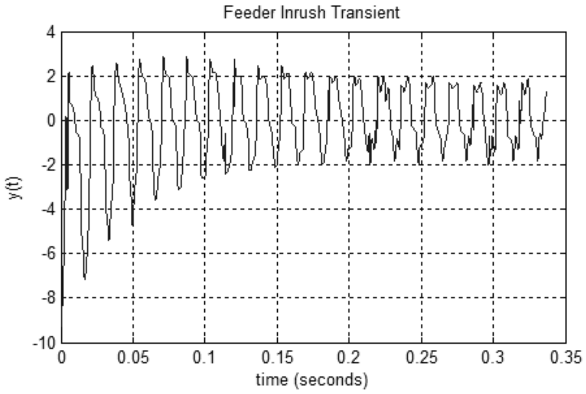

Fig. 5: Feeder inrush transient

In order to have a model for relay response to the real-world transient, the waveform is first decomposed to it's frequency components. The frequency spectra is shown in Fig. 23. Fourier transform was used to determine the spectral content.

Literature says that it takes at least 10-20% distortion to affect relay operation. The second harmonic meets this criterion in the transient input.

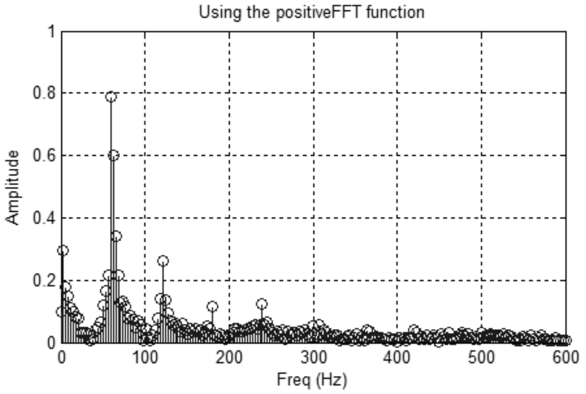

Fig. 6: Frequency spectra of the feeder inrush transient

For the G.E. DIACA5A relay, the model for fundamental and 2nd harmonic pair input is given by Eq. (2). From the data taken from the Fourier analysis, the second harmonic is found to be 37% of the magnitude of the fundamental. Using 37 as the percent distortion value x, Eq. (16) is solved to give a trip time of 0.5869 seconds. Had there been no wave distortion, x will be zero, and the trip time given by Eq. (16) will be 0.7276 seconds. The ratio of the 0.5867 sec output of the model, which we shall t, to the 0.7276 sec output without distortion, t0, will be called the distortion penalty factor. The distortion penalty factor is then multiplied to the output of the phasor models provided by the manufacturers in order to account for the effects of the distortion. The distortion factor is 0.5867/0.7276, which is equal to 0.80523. The prediction of the manufacturer's phasor model, or t_phasor, for the DIAC relay is 0.72510 seconds. Multiplying t_phasor and the penalty factor gives 0.72510 x 0.80523, which is equal to 0.58387. The product of t_phasor and penalty factor will be called t_model.

The average experimental result is 0.55747 seconds, which is very close the computed t_model (0.58387 sec). This is a significant improvement to the current phasor model prediction of 0.72510 seconds. The results for models for the other relays are shown in Table 3. These were the relays that had enough data to be modeled.

$$t_{trip}(x) = 0.525180 + 0.202420\, e^{-0.032114x} \qquad (2)$$

Where ttrip is the relay response time and x is the amount of distortion in percent.

Table 3: Using developed models on a real world inrush transient waveform

Relay	DIA	SK88	BE1B	BE1	SR	SPAJ	SEL
t	0.58589	0.49064	0.88369	0.97026	0.66770	0.63801	0.70090
t0	0.72760	0.82637	0.88377	0.96287	0.65789	0.70109	0.71041
penalty factor	0.80523	0.59373	0.99991	1.00768	1.01491	0.91003	0.98662
t_phasor	0.72510	0.79000	0.87970	0.96540	0.65400	0.71010	0.69960
t_model	0.58387	0.46905	0.87962	0.97281	0.66375	0.64621	0.69024
t_expt	0.55747	0.35960	0.74800	1.16930	0.62107	0.58980	0.48853
% error old	30.07056	119.68854	17.60695	17.43778	5.30271	20.39674	43.20415
% error new	4.73713	30.43591	17.59593	16.80409	6.87243	9.56415	41.28824

The process for computing t_model for the other relays in Table 3 is the same as the process used for the DIAC overcurrent relay previously discussed. The average of the percent errors for the proposed model is 18%. It is an improvement from the average of the previous phasor model percent errors, which is 36%. The percent error new is computed by taking the absolute value difference of t_model and the experimental measurement, t_expt. The difference is divided by t_expt and then multiplied by 100. The percent error old is computed by taking the absolute value difference of t_phasor and the experimental measurement, t_expt. The difference is divided by t_expt and then multiplied by 100. A large value of error is seen for the SEL-587 relay. A probable cause for error is the presence of significant direct current; data for which had not been characterized in previous research.

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

a) Electromechanical models reveal that it takes around 10% single harmonic distortion to affect the operating time of the relay. Electromechanical relay models have adjacent harmonics affecting the operating time in like manner.

b) Solid state models show that it takes around 10% single harmonic distortion to affect the operating time of the relay. Static analog relays have specific harmonics affecting the operating time quite differently from the rest. These harmonics differ from relay to relay.

c) Microprocessor-based models show that it takes around 20% single harmonic distortion to affect the operating time of the relay. Static digital relays are most immune to distortion, though the relatively small effects of distortion at different harmonics are more varied.

d) From the modeling of relay response time to a feeder inrush transient, it was seen that the error coming from using phasor based models can significantly be reduced by adapting the models developed through this research.

Relay transient characteristic modeling offer insight into the random behavior of relays. Obtaining more data will better validate and improve the models developed. More data from transient-based characterization will also provide even more insight.

ACKNOWLEDGMENTS

This study will not be possible without the generous support of the ERDT program and the kindness of Engr. Ronaldo G. Canseco.

APPENDIX

a.1) List of relays used in the study

1. G.E. 12IAC53A1A, G.E. 12IAC51B1A, G.E. 12IFC53A1A

2. A.B.B./W.H. CO-9/Style 264C901A07, W.H. CO-9H111N/Style 264C901A07

3. Basler BE1 – 50/51 B

4. G.E. DIACA5A

5. Siemens 7SK8854

6. A.B.B SPAJ140C

7. Basler BE1-851

8. G.E. Multidia SR-760

9. Schweitzer SEL-587

a.2) Ezyfit

The Ezyfit toolbox for Matlab enables you to perform simple curve fitting of one-dimensional data using arbitrary (non linear) fitting functions. It provides a set of command-line functions to perform curve fitting 'programmatically'.

Write-up is from the Ezyfit website, http://www.fast.u-psud.fr/ezyfit/, Version 2.30 - 5 February 2009.

a.3) g3data

g3data is used for extracting data from graphs. In publications graphs often are included, but the actual data is missing. g3data makes the extracting process much easier. It is a free software released under the GNU General Public License. It was created and maintained by Jonas Frantz <jonas.frantz(at)welho.com> .

The program may be downloaded from,
http://www.frantz.fi/software/g3data.php

REFERENCES

[1] ABB, MDAR Relay System, ABB Power T&D Company Inc, 1993

[2] ABB, SPAJ 140 C Overcurrent and Earth-fualt Relay, User's manual and Technical description, Finland: ABB Substation Automation, January 1997

[3] Baker, D.S., et al, Application Considerations of Static Overcurrent Relays: A Working Group Report, IEEE Transactions on Industry Applications, 1997

[4] Chan, S. and R. Maurer, Modelling Overcurrent Relay Characteristics, IEEE Computer Applications in Power, 1992

[5] Dalci, K. Burak, et al, Harmonic Effects On Electromechanical Overcurrent Relays, Yıldız Technical University, Electrical Engineering Department, Dogus Üniversitesi Dergisi, 2005