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# Fault Current Calculation by The Least Squares Method

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***Abstract*****-- This paper contains the analysis of the increase of fault current due to the installation of DGs or merchant plants. An index called the Average Change of Fault Current, ACF, is proposed. The ACF can be applied to indicate the contribution of the increase of fault current and to allocate the responsibility of system upgrades among the owners of DGs. The least squares method for calculating the ACF is discussed. The confidence interval of the coefficients and mean response of ACF is discussed.**

***Index Terms*****—Distributed generation, dispersed generation, power distribution, fault current calculation, average change of fault current.**

## I. Introduction

PROTECTION system planning is one of the indispensable parts of electric power system design. Analysis of fault level, pre-fault condition, and post-fault condition are required for the selection of interruption devices, protective relays, and their coordination. Systems must be able to withstand a certain limit of faults which also affects reliability indices. This paper relates to the increase of fault currents due to the addition of DGs: the appearance of distributed generation (DG), perhaps at high levels of penetration, and the effect of DG on fault currents.

Deregulation, utility restructuring, technology evolution, environmental policies and increasing electric demand are stimuli for new distributed generation. According to the US Department of Energy, DG is defined as “the modular electric generation or storage located near the point of use. Distributed generation systems include biomass-based generators, combustion turbines, thermal solar power and photovoltaic systems, fuel cells, wind turbines, microturbines, engines/generator sets and storage and control technologies. Distributed resources can either be grid connected or independent of the grid. According to the IEEE Standard 1547-2003, DG is defined as “Electric generation facilities connected to an Area Electric Power System (EPS) operator through a Point of Common Coupling (PCC); a subset of Distributed Resource (DR)” [1]. Reduction of investment in transmission and distribution system upgrades and fast installation are the major benefits to the power utilities. Many applications, such as upgrading the reliability of the power supply, peak shaving, grid support and combined heat and power (CHP), are the major benefits to distributed generation owners.

However, the appearance of co-generation, DG, and unconventional generation may result in the change of the fault response in a system. New operating conditions may occur after appearance of new generation sources in the power systems. Many types of DGs, such as fuel cells, microturbines, wind turbines, solar cells, and reciprocating engine are sold in the market. The variety of control techniques of the DGs result in different characteristics during both normal and abnormal operating conditions.

## II. Increase of fault current

Circuit breaker capability and configuration of protective relays that were previously designed for the system without DGs may not safely manage faults. In order to assess the severity (i.e., amplitude) of the increase in fault current in the system due to installing DGs, fault current analysis is done, and this procedure is standardized and considered critical. The process is lengthy and generally considered to be quite accurate. Many classical references have been written on this topic, such as [2] - [5].

This paper proposes an index called Average Change of Fault current, *ACF*. One of the applications of *ACF* is to indicate the severity of the increase of fault currents in the system due to the installation of each DG or merchant plant. The least squares method for calculating the ACF is discussed in the following sections.

$$ACF = \frac{\sum_{n=1}^{nbus} \left| \frac{I_{f,n} - I_{fDG,n}}{I_{f,n}} \right| \times 100}{(number\ of\ 69\ kVbus - 1)} \tag{1}$$

where $I_{f,n}$ is the fault current at bus $n$ before installing new DG, $I_{fDG,n}$ is the fault current at bus $n$ after installing new DGs into the system, and *nbus* is the total bus in the system. Note that

$$\left| \frac{I_{f,n} - I_{fDG,n}}{I_{f,n}} \right| \times 100$$

is the percent change of amplitude of the fault currents at the 69 kV buses.

Normally, owner of the buses with new DGs have to upgrade the fault current interrupting capability of the circuit breaker and the change of the fault current, $\Delta\left|I_f\right|$, at the slack bus is not significant. For these reasons, the buses with new DGs and system slack bus are not taking into consideration in (1).

## III. Least squares estimator concepts

Assuming that the ACF model of the system is a set of linear functions $y(x_1, x_2, x_3, \ldots x_{mk})$, the output of a linear system can be written as,

$$y_i = \sum_{i=1}^{mk} w_i x_i$$

or

$$Y = Wx, \tag{2}$$

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In (2), $Y$ is a general output vectors. For the present calculation, $Y$ will be taken to be a scalar presentation of the fault current average across a power system to which DG is added. The matrix $W$ is a one-by-$mk$ matrix (row vector) containing the linear coefficients (also known as a "weight vector"), and $x$ is an $mk$-by-one data vector. The index $m$ is the number of 12-kV buses where DG or merchant plant can be installed, $k$ is order of the linear function and $n$ is the set of data.

The error matrix, $E$, is given by comparing the output from the least squares model with the corresponding desired $n$-by-one output matrix $D$,

$$E = D - Y.$$

Note that the goal of system modeling is to minimize the sum of squares of the error. In this case, the variables to be identified to accomplish this minimization are the $w_n$ values. Therefore, the estimate of the weight vector $W$ is given as

$$\hat{W} = \left( \left( X^T X \right)^{-1} X^T \right) D \cdot \quad (3)$$

The term $\left( X^T X \right)^{-1} X^T$ is recognized as the pseudoinverse of $X$ and the notation $X^+$ is used [6], [8].

## IV. Application of the Least Squares Method

In this application, the lease square estimator is applied to calculate the ACF of the system corresponding to the impedance of DGs. The unknown system can be modeled as many different functions – in this case of the impedance of added DGs. After a search of many potential fitting functions, the following are offered as potential candidates and all are linear in the $w_n$ terms,

First order:

$$ACF = Y = \sum_{i=1}^{m} w_i \cdot \left| Z_{DG,i} \right| \quad (4)$$

Second order:

$$ACF = Y = \sum_{i=1}^{m} w_{1i} \cdot \left| Z_{DG,i} \right| + \sum_{i=1}^{m} w_{2i} \cdot \left| Z_{DG,i} \right|^2 \quad (5)$$

Third order:

$$ACF = Y = \sum_{i=1}^{m} w_{1i} \cdot \left| Z_{DG,i} \right| + \sum_{i=1}^{m} w_{2i} \cdot \left| Z_{DG,i} \right|^2 + \sum_{i=1}^{m} w_{3i} \cdot \left| Z_{DG,i} \right|^3 \quad (6)$$

Reciprocal of $DG_{imp,k}$:

$$ACF = Y = \sum_{i=1}^{m} w_{1i} \cdot \left| Z_{DG,i} \right|^{-1} \quad (7)$$

Reciprocal of $DG_{imp,k}$ squares:

$$ACF = Y = \sum_{i=1}^{m} w_{1i} \cdot \left| Z_{DG,i} \right|^{-1} + \sum_{i=1}^{m} w_{2i} \cdot \left| Z_{DG,i} \right|^{-2} \quad (8)$$

Reciprocal of $DG_{imp,k}$ cubes:

$$ACF = Y = \sum_{i=1}^{m} w_{1n} \cdot \left| Z_{DG,i} \right|^{-1} + \sum_{i=1}^{m} w_{2i} \cdot \left| Z_{DG,i} \right|^{-2} + \sum_{i1}^{m} w_{3i} \cdot \left| Z_{DG,i} \right|^{-3} \quad (9)$$

The input data and DG impedances are used to estimate $W$ which is a vector of the indicated $w$ weights above. Calculation of the weight vector, $w_{mk}$, used as in (3) is comparable to the parameter estimation techniques in [6] and [7]. Note that $Z_{DG,i}$ is the impedance of the added DG and $w_{1i}$, $w_{2i}$ and $w_{3i}$ are the coefficients of the several terms in the expansion.

## V. Timing of the Addition of DGs

The foregoing concept is that an index be utilized to determine the percentage of upgrade costs that should be equitably attributed to owners of new DGs. If a single DG is added, there is no issue on the attribution of cost. However, if several DGs are installed – more or less at the same time – it may not be clear as to who should pay for upgrade costs. The ACF concept is a standardized way to attribute costs. The envisioned concept is that costs associated with the purchase and installation of circuit protection hardware, including circuit breakers, shall be evaluated at the time that the added DGs are commissioned.

Only synchronous generator DGs are addressed in this paper – although inverter based DGs are predominant at the lower power levels.

## VI. Illustrative Examples

To illustrate the application of the proposed index, a sample system (see Fig. 1) is used to demonstrate the potential economic impact due to the high levels of DG and merchant plant penetration.

The sample system is connected to a 230 kV transmission system at bus Thunder1, considered as the system slack bus. The voltage level at 230 kV from slack bus is stepped down to 69 kV at the supply substation. The taps of substation transformer at 230 kV and the 12 kV distribution transformers usually operate higher than 1.0 p.u. to reduce the effect of voltage drop in the distribution level. The Thevenin equivalent impedance of 230 kV bus is 0.757+$j$6.183 ohms per phase.

By applying the reciprocal of $DG_{imp,k}$ cubes model,

$$\text{ACF} = \sum_{i=1}^{m} w_{1i} \cdot \left| Z_{DG,i} \right|^{-1} + \sum_{i=1}^{m} w_{2i} \cdot \left| Z_{DG,i} \right|^{-2} + \sum_{i=1}^{m} w_{3i} \cdot \left| Z_{DG,i} \right|^{-3} \quad (10)$$

the coefficient matrix, $W_{mk}$, is calculated from the database which can be generated randomly from the fault current calculation program. Number of elements of the coefficient matrix is $m$-by-$k^{th}$ order of the model. The database composes impedance of DGs in each location and ACFs of the sample system.

Assume that the DGs are installed at 6 locations: Cameron2, Signal3, Seaton2, Ealy3, Ealy4 and Sage3. The transient impedances of each DG are as shown in Table 1.

TABLE 1
LIST OF THE BUSES WITH NEW DG

| Bus name | Transient impedance of the DG (p.u.) |
|---|---|
| Cameron2 (6) | 0.005 + $j$0.81 |
| Signal3 (11) | 0.005 + $j$0.90 |
| Seaton2 (22) | 0.005 + $j$0.83 |
| Ealy3 (24) | 0.005 + $j$0.85 |
| Ealy4 (25) | 0.005 + $j$0.92 |
| Sage3 (26) | 0.005 + $j$0.84 |

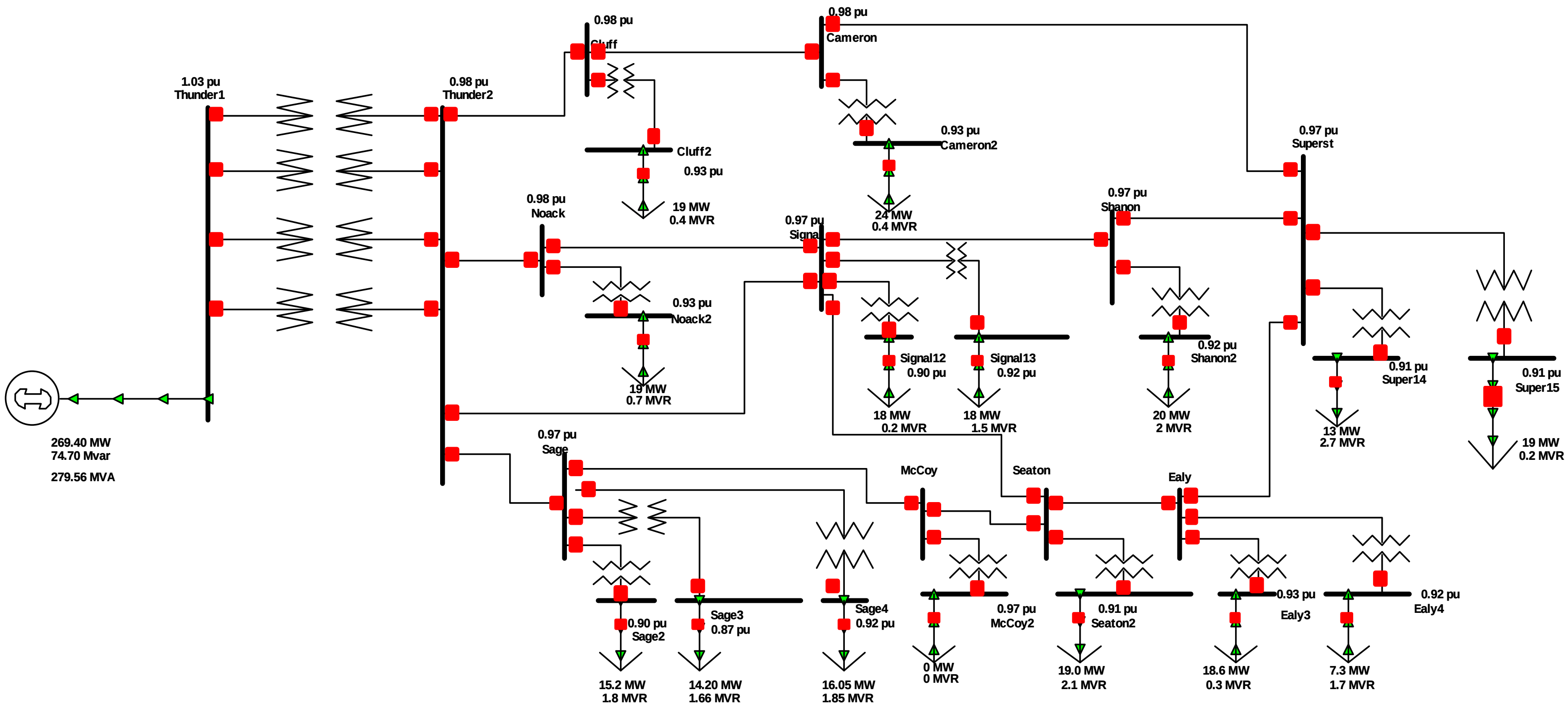


Fig. 1. Illustrative example 69 kV transmission system

In this calculation, the least squares estimator model is created from 500 cases. Impedances of DGs installed at 12-kV buses are generated randomly with uniformly distributed under the same base MVA. The database is uniformly collected and used to calculate the coefficients of the model by replacing into (3). The coefficient matrix of the illustrative system is,

$$W_{1i}=\begin{bmatrix}2.2048\\2.5609\\1.7878\\2.3637\\2.3148\\2.7164\\2.4916\\2.3671\\2.3834\\2.6878\\2.8195\\2.8508\\2.3576\\2.2561\end{bmatrix}\quad W_{2i}=\begin{bmatrix}-1.1148\\-1.2409\\-0.8427\\-1.1276\\-1.1037\\-1.1208\\-1.1090\\-1.1408\\-1.2601\\-1.2799\\-1.1144\\-1.4519\\-1.2003\\-1.1449\end{bmatrix}\quad W_{3i}=\begin{bmatrix}0.2317\\0.2641\\0.1711\\0.2298\\0.2259\\0.2100\\0.2113\\0.2252\\0.2692\\0.2643\\0.2006\\0.2991\\0.2523\\0.2447\end{bmatrix}.$$

The ACF of the system as in (10) is

$$\text{ACF}=\sum_{i=1}^{m} w_{1i}\cdot\left|Z_{DG,i}\right|^{-1}+\sum_{i=1}^{m} w_{2i}\cdot\left|Z_{DG,i}\right|^{-2}+\sum_{i=1}^{m} w_{3i}\cdot\left|Z_{DG,i}\right|^{-3}.$$

$= 10.63$ %.

Note that the ACF from the conventional fault current calculation is 10.87 %. The error from the least squares estimator compared to the conventional fault current calculation is 2.25 %.

Equation (10) gives the relation between the impedance of DGs in the system and the ACF. Accuracy of the least squares model can be measured by the norm of error squares,

$$\|E\| = \frac{\|ACF_{conv}-Y\|}{\|Y\|}\ \text{p.u.}$$

or

$$\|E\| = \frac{\|ACF_{conv}-W_{mk}\cdot X\|}{\|W_{mk}\cdot X\|}\ \text{p.u.},$$

where $ACF_{conv}$ is the average change of fault current from the conventional fault current calculation.

From all models in (4) to (9), the reciprocal of $DG_{imp}$ cubes as in (9) gives the least norm of error squares. The norm of error squares of each model is shown in Table 2.

TABLE 2 NORM OF ERROR SQUARED FOR ILLUSTRATIVE EXAMPLE

| Model | Equation | Norm of error squared* |
|---|---|---|
| First order | (3) | 0.1300 |
| Second order | (4) | 0.0411 |
| Third order | (5) | 0.0112 |
| Reciprocal of $\left\|Z_{DG,n}\right\|$ | (6) | 0.0575 |
| Reciprocal of $\left\|Z_{DG,n}\right\|^2$ | (7) | 0.00897 |
| Reciprocal of $\left\|Z_{DG,n}\right\|^3$ | (8) | 0.00155 |

* expressed as a fraction, e.g., 0.13 = 13.0%

Note that (10) can be independently written as 14 components according to fourteen 12 kV buses. Each component, called "Bus ACF", relates to the contribution of the DG to the ACF. The plot of Bus ACF and the total ACF is shown in Fig. 2. For instance, the contribution of the DG at bus 6 (Cameron2) and 11 (Signal3) to ACF are, respectively,

$$ACF_6 = 2.5609\cdot\frac{1}{\left|Z_{DG,4}\right|}-1.2409\cdot\frac{1}{\left|Z_{DG,4}\right|^2}+0.2641\cdot\frac{1}{\left|Z_{DG,4}\right|^3} \quad (11)$$

$$ACF_{11} = 2.3148\cdot\frac{1}{\left|Z_{DG,11}\right|}-1.1037\cdot\frac{1}{\left|Z_{DG,11}\right|^2}+0.2259\cdot\frac{1}{\left|Z_{DG,11}\right|^3} \quad (12)$$

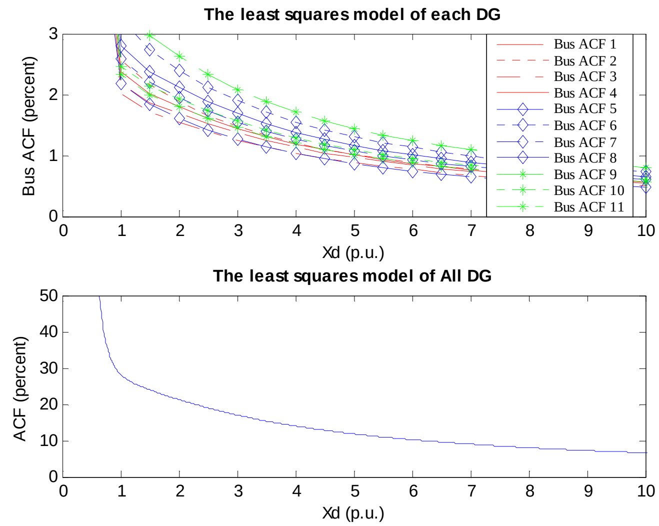


Fig. 2 Plots of the bus ACF and the total ACF

## VII. Confidence Interval of the Least Squares Estimator Coefficient

Assuming that the errors of the least squares estimator model are normally and independently distributed with mean zero and variance, $\sigma_e^2$. The coefficient matrix, $\hat{W}$, is normally distributed with the mean vector $W$ and the covariance matrix $\sigma_e^2(X'X)^{-1}$. For the same reason, the marginal distribution of any least squares estimator, $\hat{w}_{mk}$, is normal with mean $w_{mk}$ and variance $\sigma_e^2 C_{jj}$, where $C_{ii}$ is the $i$th diagonal element of the $(X'X)^{-1}$ matrix. Therefore, the 100(1-α) percent confidence interval for the least squares estimator coefficients $w_{ii}$, $i = 1,\ldots, mk$, is

$$\hat{w}_i - t_{\alpha/2,n-p}\sqrt{\hat{\sigma}_e^2 C_{ii}} \le w_i \le \hat{w}_i + t_{\alpha/2,n-p}\sqrt{\hat{\sigma}_e^2 C_{ii}} \quad (13)$$

where $t_{\alpha/2,n-p}$ is the value from $t$-distribution, $n$ is the number of all historical data, $p$ is number of coefficient of the least squares estimator and $\sigma_e^2$ is the estimation of variance of errors. The estimation of variance of errors, $\sigma_e^2$, is,

$$\hat{\sigma}_e^2 = \frac{SS_{\text{Res}}}{n-p} = \frac{D'D-\hat{w}_n^T X^T D}{n-p},$$

where $SS_{Res}$ is the residual or error sum of squares [8].

Applying (11), the 95 percent confidence intervals on the coefficients of the ACF model for the illustrated system, Fig. 1, are shown in Table A1.

As part of a further discussion of the confidence in the estimate, define a particular situation when the input of the ACF model is

$$x_0 = \begin{bmatrix} x_{11} & \cdots & x_{1m} & x_{21} & \dots & x_{2m} & \cdots & x_{km} \end{bmatrix}^T .$$

For example, if considering the reciprocal of $\left|Z_{DG,i}\right|^3$ as the ACF model, the input matrix of the ACF model is,

$$x_0 = \begin{bmatrix} \left|Z_{DG,1}\right|^{-1} \\ \vdots \\ \left|Z_{DG,m}\right|^{-1} \\ \left|Z_{DG,1}\right|^{-2} \\ \vdots \\ \left|Z_{DG,m}\right|^{-2} \\ \left|Z_{DG,1}\right|^{-3} \\ \vdots \\ \left|Z_{DG,m}\right|^{-3} \end{bmatrix}.$$

The ACF can be calculated at a particular point by applying (8),

$$A\hat{C}F = \sum_{n=1}^{m} \hat{w}_{1n} \cdot \left|Z_{DG,n}\right|^{-1} + \sum_{n=1}^{m} \hat{w}_{2n} \cdot \left|Z_{DG,n}\right|^{-2} + \sum_{n=1}^{m} \hat{w}_{3n} \cdot \left|Z_{DG,n}\right|^{-3}$$

The variance of the $A\hat{C}F$ is

$$Var(A\hat{C}F) = \sigma^2 x_0' (X'X)^{-1} x_0 .$$

Therefore, 100(1-α) percent confidence interval on the mean response of the ACF model with $x_0$, $E(ACF|x_0)$, as the input is [38],

$$A\hat{C}F_0 \pm t_{\alpha/2,n-p} \sqrt{\hat{\sigma}_e^{\,2} x_0' C_{nn} x_0} . \qquad (14)$$

For instance, the 95 percent confidence interval of ACF of the illustrative system with new DGs, $E(ACF|x_0)$, shown in Table 3 is,

$$10.63 \pm t_{0.025,467} \sqrt{\hat{\sigma}_e^{\,2} x_0' C_{jj} x_0} ,$$

or

$$10.53 \le E(ACF|x_0) \le 10.819 .$$

There is ninety five percent that the true ACF of this Case stays in the indicated interval. Table 4 shows the confidence interval of the ACF value of the illustrative system with various percent confidence, α.

## VIII. Allocation of the Responsibility for the System Upgrades to the Owner of DGs

This section proposes a technique to allocate the responsibility of each DG owner due to the system upgrades by applying the ACF index. Theoretically, the owner of DGs should share the cost for the system upgrades, depending on the severity of the change of fault created by their own DGs. With reference to the illustrated system, six DGs are installed at the 12 kV bus. From the conventional fault current calculation, as the consequence of installing these DGs, the CBs at 2 locations need to be upgraded. The contributions of the DG at each bus are calculated as in (11) and (12).

Table 3 Confidence interval of the coefficients of the ACF model for the illustrative example

| Model coefficient, $w_i$ | Ninety five percent confidence interval | $\dfrac{95\%\ confidence\ interval}{Coefficient\ w_i}$ |
|---|---|---|
| 2.2048 | ± 0.2650 | 0.1202 |
| 2.5609 | ± 0.2433 | 0.0950 |
| 1.7878 | ± 0.2457 | 0.1374 |
| 2.3637 | ± 0.2564 | 0.1085 |
| 2.3148 | ± 0.2470 | 0.1067 |
| 2.7164 | ± 0.2310 | 0.0850 |
| 2.4916 | ± 0.2503 | 0.1005 |
| 2.3671 | ± 0.2548 | 0.1076 |
| 2.3834 | ± 0.2554 | 0.1072 |
| 2.6878 | ± 0.2830 | 0.1053 |
| 2.8195 | ± 0.2372 | 0.0841 |
| 2.8508 | ± 0.2695 | 0.0945 |
| 2.3576 | ± 0.2477 | 0.1051 |
| 2.2561 | ± 0.2572 | 0.1140 |
| -1.1148 | ± 0.2195 | 0.1969 |
| -1.2409 | ± 0.2001 | 0.1613 |
| -0.8427 | ± 0.2009 | 0.2384 |
| -1.1276 | ± 0.2126 | 0.1885 |
| -1.1037 | ± 0.2021 | 0.1831 |
| -1.1208 | ± 0.1879 | 0.1676 |
| -1.1090 | ± 0.2057 | 0.1855 |
| -1.1408 | ± 0.2113 | 0.1852 |
| -1.2601 | ± 0.2104 | 0.1670 |
| -1.2799 | ± 0.2342 | 0.1830 |
| -1.1144 | ± 0.1945 | 0.1745 |
| -1.4519 | ± 0.2254 | 0.1552 |
| -1.2003 | ± 0.2052 | 0.1710 |
| -1.1449 | ± 0.2126 | 0.1857 |
| 0.2317 | ± 0.0579 | 0.2499 |
| 0.2641 | ± 0.0523 | 0.1980 |
| 0.1711 | ± 0.0521 | 0.3045 |
| 0.2298 | ± 0.0559 | 0.2433 |
| 0.2259 | ± 0.0526 | 0.2328 |
| 0.2100 | ± 0.0485 | 0.2310 |
| 0.2113 | ± 0.0537 | 0.2541 |
| 0.2252 | ± 0.0556 | 0.2469 |
| 0.2692 | ± 0.0552 | 0.2051 |
| 0.2643 | ± 0.0617 | 0.2334 |
| 0.2006 | ± 0.0505 | 0.2517 |
| 0.2991 | ± 0.0601 | 0.2009 |
| 0.2523 | ± 0.0541 | 0.2144 |
| 0.2447 | ± 0.0559 | 0.2284 |

Table 4 Percent confidence and their confidence intervals for the ACF for the illustrative example

| Percent confidence interval | Confidence interval, $E(ACF\|x_0)$ |
|---|---|
| 98 | 10.63 ± 0.21 |
| 95 | 10.63 ± 0.18 |
| 90 | 10.63 ± 0.15 |
| 80 | 10.63 ± 0.12 |

The owners of DG should pay for the cost of upgrading the protection system, such as installation cost of circuit breakers and fuses, proportional to the $ACF_i$. For this reason, the cost for each owner of DG is distributed according to the following allocation, *Price to the owner of DG at bus i*

$$= \frac{Total\ cost\ \ for\ system\ \ upgrades}{\sum_{i}^{N} ACF_i} \cdot ACF_i \qquad (15)$$

where $N$ is the number of the bus with DG.

Assuming that the cost of upgrading the CB at each of two locations is 50,000 dollars, that is, in (15) the total upgrade cost is 100,000 dollars. Then, the costs of upgrading the system for each owner of a DG are shown in Table 5.

In (15), it is assumed that the entire CB upgrade costs should be assigned to the DG owners. If some fraction $F$ of the total cost is to be paid by the utility company, then 1-$F$ is paid by the DG owner,

*Price to the owner of DG at bus i*

$$= (1-F) \cdot \frac{Total\ cost\ \ for\ system\ \ upgrades}{\sum_{i}^{N} ACF_i} \cdot ACF_i \cdot \qquad (16)$$

TABLE 5 COST FOR UPGRADES THE SYSTEM DUE TO INSTALLING NEW DGS

| Bus name | Cost of upgrading the system, dollar |
|---|---|
| Cameron2 (6) | 16,639.98 |
| Signal3 (11) | 15,161.50 |
| Seaton2 (22) | 17,355.68 |
| Ealy3 (24) | 19785.29 |
| Ealy4 (25) | 16,639.98 |
| Sage3 (26) | 14,417.55 |

## IX. CONCLUSIONS

Contribution of the increase of fault current due to installation of DG and merchant plant can be indicated by applying the ACF index. The concept is that several DGs are added more-or-less simultaneously, and there is a need to assign the cost of protective upgrades due to the commissioning of the several DGs. A model is used to obtain the ACF index which is a percentage attribute to owners of the new DGs. The least squares method can be applied to calculate the coefficients of the ACF model. In an illustrative example, by replacing only the impedance of new DGs in the least squares method model, the ACF from the least squares method of the illustrative system is 9.635 percent. The error of the least squares method from the precise calculation is 2.48 percent in that illustration. The general conclusion on the basis of testing is that the ACF is accurate in the 10% range.

One of the applications of the ACF index is to allocate the cost of upgrading the system. The cost of upgrades the system for each owner of DG mainly depends on the transient impedance of the DGs and the configuration of the system.

## X. ACKNOWLEDGEMENT

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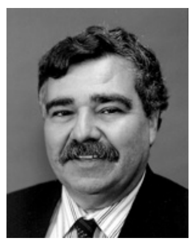

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