Analytical Representation of the Relationship Between Generator Design and System Fault Behavior

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***Abstract*—This paper presents the development and application of an analytical method for formalizing the dependence of the behavior of a large power system under fault conditions on the equivalent impedance presented by a single generator. After selecting an appropriate generator model, it is demonstrated that network-wide fault behavior can be expressed as a rational function of the equivalent impedance presented by a single generator under fault conditions. This representation simplifies the identification and depiction of constraints imposed by system configuration on the ability of a generator replacement or augmentation to affect fault behavior. The effectiveness of the proposed method is confirmed by considering the three-phase fault currents produced in a six-bus test system. In addition, the new analytical method is extended to obtain a numerical estimate of the maximum possible change in fault behavior that could result from a generator replacement or augmentation. Overall, the new approach aids in the evaluation of the suitability of generator modification or augmentation schemes.**

***Index Terms*—Power generation faults, power generation planning, power system faults, rational functions.**

I. Introduction

POWER system fault behavior is controlled by the interaction between the connected rotating machinery and system configuration. The IEEE Standards 399 [1] state that the magnitude and duration of short-curcuit currents are essentially controlled by the behavior of rotating machinery in the system and its electrical proximity to the fault point. In transmission systems large synchronous generators dominate the connected rotating machinery. These generators form the main source of fault current, with their contributions limited or constrained by system topology.

The dependence of network fault behavior on both generator construction and system topology is readily acknowledged, but rarely defined explicitly. Work by Tleis [2] and Boley [3] highlights the interplay between generator capacity and system topology that controls fault behavior. In neither reference, however, is the nature of this relationship defined precisely. Alternatively, Canay *et al.* [4] have demonstrated the controlling influence of generator behavior on the shape of the fault current waveforms. Nonetheless, Canay's observations are relevant for near-to-generator fault conditions only. This suggests that a formal understanding of the relationship between generator behavior and fault performance, valid for fault locations across a large system, is still not available.

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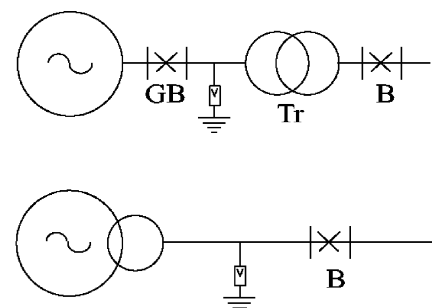

Fig. 1. Comparative configurations of conventional generator and transformer with Powerformer [6].

Conversely, an understanding of the link between generator construction and network fault behavior is essential when replacing existing generation capacity with novel or innovative generator designs. For example, the introduction of Powerformer, the high-voltage generator unveiled by ABB Corporate research in 1997 [5], could have a profound impact on network fault behavior. Powerformer is able to generate electricity at transmission voltage levels, so does not require a dedicated step-up transformer. The configurations of a conventional generator and Powerformer are shown in Fig. 1.

The impedance presented to the rest of the network by Powerformer may be significantly different to that presented by the conventional generator-transformer combination. A new technique is required to illustrate the impact of such changes to generator design on system-wide fault behavior. It is, however, not physically possible to change to the design of an existing generator. Instead, the phrase "change in generator design" will be used in this paper to describe the variation in the equivalent impedance presented to the system by a generator that results from the replacement or augmentation of existing generation capacity.

This paper describes the formulation and application of a new analytical method, called the "breakpoint separation approach". The "breakpoint separation approach" is based on a distinct algebraic representation of the relationship between generator design and system fault behavior. It provides a means to identify

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and visualise system-imposed limits on the ability of generator design selection to affect fault behavior. While some of the these issues have been addressed in a piecemeal approach in previous works by the authors [7]–[10], this paper develops the relationships between generator design and the different facets of fault behavior in terms of a unified theoretical framework.

The development of this representation, incorporating appropriate generator and system models, is addressed in the initial part of the paper. The majority of the paper will focus on the significance of the format of the developed algebraic representation. Only limited numerical validation of the theoretical relationships derived is provided. Instead, extensive verification will be provided in subsequent papers, in which the new approach is used to characterize the impact of replacing a conventional generator with Powerformer.

II. Generator Model for Representing Design Variations

Under fault conditions, a generator can be modeled in two different ways. It can be represented as a set of differential equations for time-domain fault calculations. Alternatively it can be modeled as voltage source behind a constant impedance for quasisteady fault analysis methods. It was felt that generator design variation could be represented clearly using the second simpler model, especially when using its Norton's equivalent, as is shown in Fig. 2.

From the point of view of the system, the generator appears as a variable impedance link to ground and a dependent current source, both external to the original network, as shown in Fig. 2. The equivalent impedance, Z_G, represents the assumed flux distribution within the generator under fault conditions. The magnitude of the dependent current source is fixed by the need to maintain the required terminal of $V_{T(0)}$ before the inception of the fault.

The main reason for using the simple model is that it will allow different generator design changes to be represented in a common manner. The model illustrated is a simplification of the full time domain model. Consequently, changes to the equivalent impedance can reflect variations in any of the parameters used in the complex model required for time-domain fault analysis. These parameter variations could be as a result of either the time-dependent behavior of a generator or pronounced physical modifications to generator configuration. In either case, the changes will be seen as merely variations in the equivalent impedance and consequent variations in the current injection into the system.

An additional feature of the selected model is the ease with which both generator modifications and augmentations can be illustrated and compared. Fig. 2. shows the connection of a "new" generator to augment an existing system. The modification of an existing generator can be represented in a comparative fashion, by connecting a "new" generator in parallel to an existing generator, such as is shown in Fig. 3. Using this approach, the modification of an existing generator can be treated in the same way as the connection of a "new" generator. This will ensure more general applicability for the approach presented in this paper.

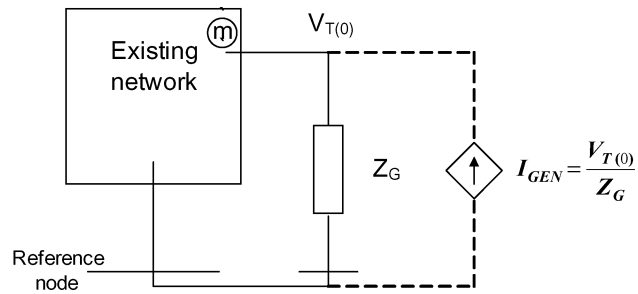

Fig. 2. Representation of interface between single generator and remainder of network for fault analysis.

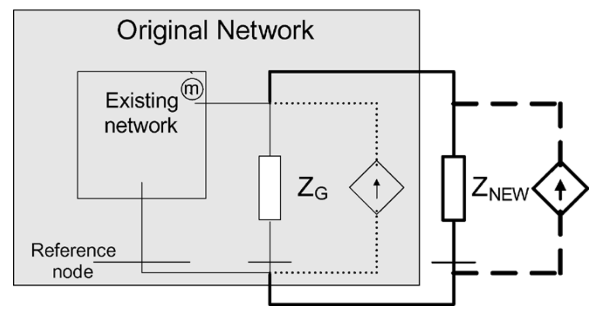

Fig. 3. Representation of modification of design of existing generator.

III. Illustrating Impact of Generator Design Change on Network Fault Behavior

The selected generator model must be integrated into an analytical representation of network-wide behavior under fault conditions. This requires an understanding of the process of fault analysis. Only then will it be possible to choose the method that can best represent the impact of generator design changes in a concise algebraic form.

Brandwajn and Tinney [11] describe fault analysis as "*a series of linear steady-state network problems with constant excitation and small localized changes in topology*". Each different fault condition involves the solution of an equation of the form

$$[Y + \Delta Y][V'] = [I] \tag{1}$$

where $[Y]$ and $[I]$ have their usual meaning. The presence of the fault is indicated by the network modification. The process of fault analysis is the determination of network voltages resulting from this modification.

Representing the influence of changing generator design on network fault behavior involves the illustration of two different network modifications: the modification of generator design and the subsequent system modification resulting from the fault. Regrettably, these two modifications cannot be incorporated into a single network solution. The selected generator model has an enforced dependence between machine configuration and its ability to feed system faults. In contrast, the fault analysis process, summarized by (1), requires constant and independent current injections into the system. Consequently, the impact of generator design changes must be incorporated into system configuration before calculating network fault behavior.

The ease with which variable generator designs can be incorporated into network fault behavior will depend upon the chosen process of fault analysis. The various methods of fault analysis can be classified into two broad categories. Laughton [12] and Majumdar [13] describe these two solution classes as the "distributed source" method and the "source transformation" method respectively. These different methods define the contrasting approaches to obtaining fault voltages.

The "distributed source" approach obtains network fault voltages by direct solution of (1). Examples of this approach are described by Laughton [12] and also by Teo and He [14]. Changes in generator design can be incorporated into this method by updating both the admittance matrix representation of the system and the nodal current injections, before solving for the network fault voltages. The main drawback of this approach is that it is difficult to retain the identity of generator changes in the final solution of network fault conditions. Fault voltages are obtained using either matrix inversion or Gaussian elimination. An analytical approach to these processes would become cumbersome as network size increases.

The contrasting "source transformation" method calculates fault behavior as the combination of the pre-fault voltages and the voltage changes produced by the fault. The procedures used to calculate these voltage changes range from a circuit analysis based approach, described by Stagg and El-Abiad [15], to compensation based methods, such as used by Brandwajn [11], Alvardo [16], or van Amerongen [17].

It is easier to represent variable generator designs using the source transformation approach. The selected generator model does not affect the pre-fault voltages. The impact of generator design changes is reduced to assessing the effect of the connection of a "new" link external to the original network, as shown in Fig. 2., on the configuration of the whole network.

The addition of the single "new" link to the reference node, which is not coupled to any other branches in the network, can be handled using the step-by-step impedance matrix construction algorithms, such as described by both El-Abiad [18], [19] and Brown *et al.* [20]. Completing this process algebraically will ensure the influence of generator design changes on system configuration is clearly represented. For example, as described in earlier work by the authors [7], [8], the connection of a "new" generator at bus M will affect the transfer impedance between two buses K and L according to

$$Z_{KL,new} = Z_{KL} - \frac{Z_{KM} Z_{ML}}{Z_G + Z_{MM}}. \quad (2)$$

All transfer and driving point impedances in (2) refer to the existing network to which the "new" generator is connected. In contrast, Z_G represents impedance of the "new" generator that is augmenting or modifying existing generation capacity. The algebraic nature of (2) ensures its structure is independent of network configuration or the point of connection of the "new" generator.

Equation (2) can be used to develop expressions for network fault parameters in which the impact of any changes to generator design will be clearly visible. The fault current produced by a bolted three-phase fault at some bus Kin the original network is given by

$$I_K = \frac{V_{K(0)}}{Z_{KK}} \quad (3)$$

where $V_{K(0)}$ represents the voltage at the faulted bus before the initiation of the fault. After adding the "new" generator connected at bus M, representing either the modification or augmentation of existing generation capacity, (3) becomes

$$I_K = \frac{V_{K(0)}}{Z_{KK} - \frac{Z_{KM} Z_{MK}}{Z_G + Z_{MM}}}. \quad (4)$$

It is clear that fault behavior in the modified network is a function of both original network configuration and the design of the "new" generator. Again, the general nature of the expression means that it is applicable throughout a network and is not reliant on specific system configuration.

IV. Significance of Algebraic Representation of Generator Design Changes

While there is no doubt that (4) highlights the dependence of network fault behavior on generator design, there are more informative ways to express this relationship. In the authors' earlier publications [7], [8], it was demonstrated that (4) can be re-written according to

$$I_K = \frac{V_{K(0)}}{Z_{KK}} \left\{ \frac{Z_G + Z_{MM}}{Z_G + Z_{MM} - \frac{Z_{KM} Z_{MK}}{Z_{KK}}} \right\}. \quad (5)$$

Expressing the relationship in this form leads to a more formal understanding of the interaction between generator design and system configuration that controls fault behavior.

The advantage of this format is that (5) now illustrates that the fault current in the modified network can be expressed as an *analytic function* of the impedance of the "new" generator. Equation (5) is an example of what Ahlfors [21] describes as a *rational function*. By recognizing this correspondence it is possible to make use of *complex analysis* to understand the relationship between generator design and fault behavior. In particular, the properties and behavior of similar rational functions, such as transfer functions used to describe the control of a linear time-invariant system, can be used to describe the influence of generator design on fault behavior.

For instance, consider (5) where the relationship between generator design and fault current is expressed as a product of two terms. The first term represents the fault current produced at bus K before the addition of the "new" generator. It is analogous to the steady-state gain of a transfer function.

The analogy can be continued by considering the second term of (5). This term illustrates the change in fault behavior due to the presence of the "new" generator. It is a mathematical representation of the interplay between generator design and system configuration that governs fault behavior.

The important features of the second term, however, are its *breakpoints* in the complex impedance plane. These include a zero located at

$$Z_G = -Z_{MM} \quad (6)$$

and a pole located at

$$Z_G = -Z_{MM} + \frac{Z_{KM} Z_{MK}}{Z_{KK}}. \quad (7)$$

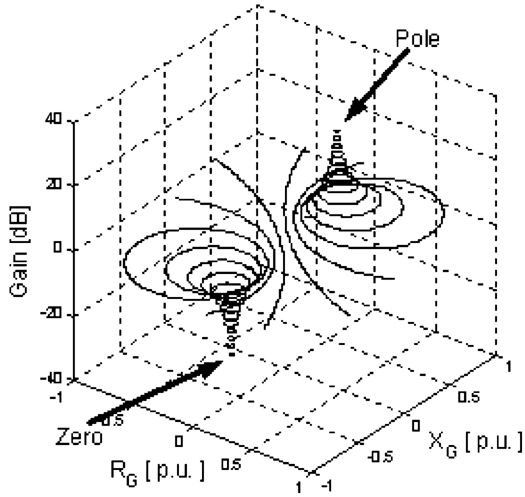

Fig. 4. Proportional increase in fault current produced by connection of "new" generator with varying equivalent impedance.

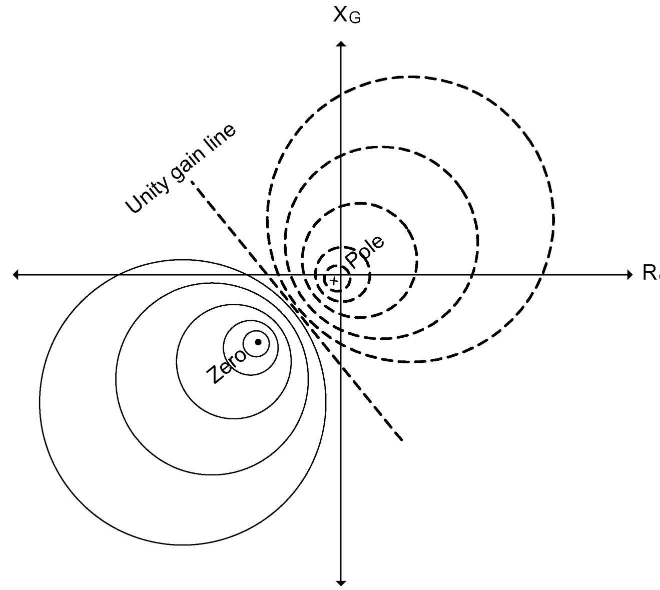

Fig. 5. Circles of constant proportional variation in fault behavior.

The position of these breakpoints is controlled by the configuration of the existing network to which the "new" generator is connected. Thus, as will be emphasized in the following sections, the location and separation of the breakpoints will help explain the limits imposed by system configuration on the influence of the "new" generator.

A. Importance of Breakpoint Location

The location of the breakpoints is important. They define the designs of the "new" generator that will lead to pronounced changes in fault behavior. This is demonstrated in Fig. 4.

Fig. 4. illustrates the fault current produced at a single point in the modified network for different equivalent impedances of the "new" generator. It is an example of the constraints imposed by system configuration on the ability of generator design selection to control fault behavior. The proximity of the generator designs to the breakpoints will determine whether the "new" generator has a significant impact. As such, breakpoints summarize the way in which the existing system limits the impact of the generator modification.

B. Importance of Breakpoint Separation

In addition to breakpoint location, the separation of the breakpoints of (5), is also important. This is underlined by attempting to find a set of generator designs leading to some constant level of fault behavior.

To illustrate this, consider the set of generator designs leading to a constant level of fault current produced by a fault at bus K in the modified network. The magnitude of fault current produced is given by the absolute value of (5). A constant magnitude of fault current will be produced at bus K for all generator fault impedance $\mathrm{Z_G}$ for which

$$G = \left| \frac{Z_G + Z_{MM}}{Z_G + \left(Z_{MM} - \frac{Z_{KM} Z_{MK}}{Z_{KK}} \right)} \right| \tag{8}$$

is a constant. This, in turn, is equivalent to

$$G = \frac{|Z_G - zero|}{|Z_G - pole|} \tag{9}$$

remaining constant.

It is stated by Ahlfors [21] that (9) defines a series of circles whose limit points are the breakpoints of this expression. An example of these circles is shown in the following Fig. 5.

In the authors' previous work [10] the equation for these circles was determined as

$$\left(R_G - \frac{G^2 R_P - R_Z}{G^2 - 1} \right)^2 + \left(X_G - \frac{G^2 X_P - X_Z}{G^2 - 1} \right)^2 = \left(\frac{G(R_P - R_Z)}{G^2 - 1} \right)^2 + \left(\frac{G(X_P - X_Z)}{G^2 - 1} \right)^2 \tag{10}$$

where $\mathrm{R_G}$, $\mathrm{X_G}$, $\mathrm{R_Z}$, $\mathrm{X_Z}$, and $\mathrm{R_P}$, $\mathrm{X_P}$ represent the real and reactive components of: the generator's equivalent impedance; the complex zero; and the complex pole respectively.

Up to this point, the significance of breakpoint separation is still not apparent. The radius of each of the circles in Fig. 5, however, can be re-written in the form of

$$\sqrt{\left(\frac{G}{G^2 - 1} \right)^2 ((R_P - R_Z)^2 + (X_P - X_Z)^2)} = \frac{|G||\Delta|}{|G^2 - 1|} \tag{11}$$

where

$$\Delta = pole - zero \tag{12}$$

represents the vector separation between the two breakpoints. This illustrates that for any given level of desired fault behavior, the size of the circular locus of generator designs that will produce the necessary modification is proportional to the separation between the relevant breakpoints, Δ.

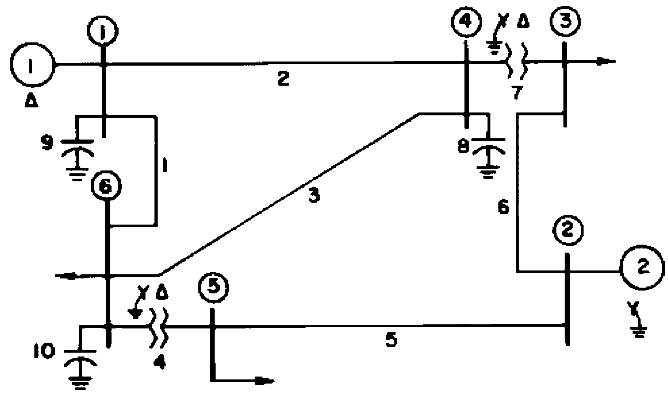

Fig. 6. Six—bus test system.

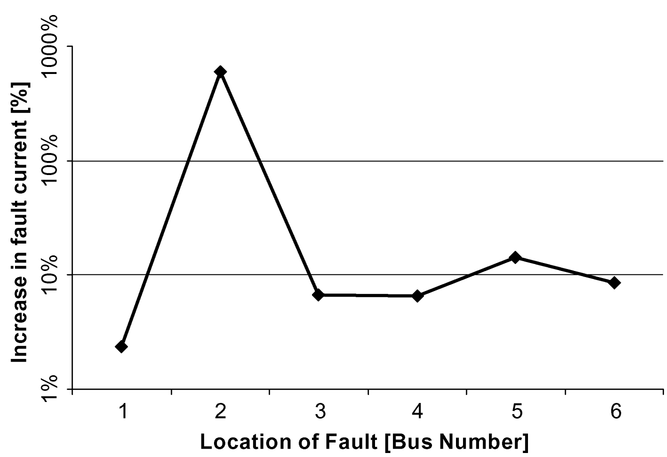

Fig. 7. Increase in current produced by faults at each bus resulting from reduction in sub-transient impedance of generator at bus 2.

The implication is that the greater the magnitude of distance between the breakpoints, $|\Delta|$, the greater the range of generator designs that could affect network fault behavior. In other words, the magnitude of breakpoint separation $|\Delta|$ is representative of the sensitivity of the relevant fault condition to generator design selection.

This relationship can be demonstrated by addressing the impact of generator design changes in a small test system. Consider the modification of the generator connected at bus 2 in the six-bus test system shown in Fig. 6. The details of this test system can be found in Anderson's text book [22].

Originally the sub-transient impedance of the generator connected at bus 2 was $0.03 + j0.48$ p.u., when specified on the system base of 100 MVA. The sub-transient impedance of this generator was reduced to the perhaps unrealistic level of $0.031\,25 + j0.05$ p.u. This pronounced generator design modification, however, will help amplify any trends in fault behavior change. In any case, the fault current produced by a bolted three-phase fault at each bus in the modified network was determined. Fig. 7 shows the increase in fault currents resulting from the change in generator design.

It is possible to determine the separation of breakpoints, Δ, that corresponds to each of the different fault locations. The variation in the magnitude of this parameter is illustrated in the following Fig. 8. The correspondence between Fig. 7 and Fig. 8

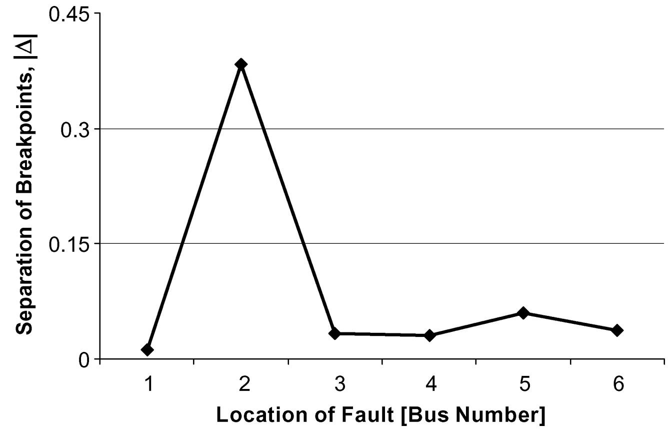

Fig. 8. Separation of breakpoints for bolted three-phase faults at each bus.

suggests that the separation of breakpoints, $|\Delta|$, is a good indicator of the potential sensitivity of fault behavior to changes in generator design.

Equations (6) and (7) indicate that $|\Delta|$ is purely a function of the configuration of the network to which the "new" generator will be connected. It is shown in Fig. 3 that the modification of an existing generator can be viewed as the connection of a "new" generator external to the original network. Consequently, the values of $|\Delta|$ shown in Fig. 8 have been determined by applying (6) and (7) to the original impedance matrix as described by Anderson [22]. As a result, Fig. 8 provides a succinct illustration of the limitations imposed by network configuration on the ability of changes to the design of the generator at bus 2 to affect fault behavior.

C. Regional Influence of Single Generator

The magnitude of the separation of the breakpoints, $|\Delta|$, can highlight fault conditions where generator design changes have a significant influence on fault behavior. By evaluating $|\Delta|$ for all fault incidents throughout the network, the fault conditions where generator design selection controls fault behavior can be located. This is the "region of control" of the generator, outside of which fault behavior will remain unaffected by generator design changes. Again, the network is limiting the ability of generator design selection to control fault behavior. The separation of the breakpoints provides a suitable means of visualizing these limits.

D. Identification of Generator Designs for Satisfactory Fault Behavior

To this point, the location and separation of the breakpoints has been used primarily to determine the sensitivity of different fault conditions to generator design selection. By application of (10) directly, it is possible to use the breakpoints to determine a set of generator designs that produce satisfactory fault behavior. The required process is described in the authors' earlier work [10]. It can be contrasted with a method outlined by Ryckaert and Ghijselen *et al.* [23] for identifying load parameters necessary to damp harmonics. It is felt that formulation proposed in this paper is a more general approach. By calculating the range of suitable generator designs using the identified breakpoints, a common methodology can be used for different fault parameters. This allows a unified treatment of different fault parameters.

E. The Breakpoint Separation Approach—A Summary

The preceding discussion has outlined a generalized approach for determining the limits imposed by network configuration on the ability of generator design changes to influence fault behavior. It has been shown that these limits can be represented using the location and separation of the breakpoints of rational functions such as (5). The limits affect:

1) the range of generator designs that produce the most pronounced variation in network fault behavior;
2) the sensitivity of fault behavior at a given location to the design of a specific generator;
3) the range of fault locations surrounding a generator's point of connection where network behavior is sensitive to generator design;
4) a set of generator designs allowing satisfactory system behavior to be maintained.

This generalized method, which has been called the "breakpoint separation approach", will make it much simpler to understand the impact of generator design changes.

Importantly, these observations were derived, not from a precise knowledge of breakpoint location, but from merely recognizing the existence of the breakpoints. In other work by the authors, relationships of a similar format to (5) are developed for the voltage disturbance, generator fault contributions and line currents produced under balanced fault conditions [7]–[9]. Single line-to-ground fault currents can also be expressed in a comparative fashion [10]. It would appear then that the "breakpoint separation approach" is a powerful tool for obtaining a general understanding of the link between generator design and network fault behavior.

V. Using Breakpoints to Characterise Realistic Generator Design Changes

In its original form, the "breakpoint separation approach" has some limitations. The basic separation of breakpoints, Δ, can act as a measure of the sensitivity of network fault behavior to generator design changes. This, however, is provided the "new" generator can take on any design on the entire complex impedance plane.

In reality, not all generator designs can be physically implemented. The "breakpoint separation approach" must be adapted to address physically realizable generator designs.

When considering the influence of the "new" generator, which is restricted to physically realizable designs only, the separation and location of the breakpoints are both important. Breakpoint separation controls the proliferation of generator designs that could exert significant control on network fault behavior. The location of the breakpoints, though, will determine the coincidence between the sensitive and physically realizable generator designs. These twin constraints can be addressed in two different ways.

The most explicit representation uses (10) to determine the distribution of generator designs that produce the desired fault behavior. The distribution of suitable generator designs can then be compared with the range of physically realisable generator parameters. This approach, while providing the most explicit solution, will be computationally demanding.

A. Normalization of Breakpoint Separation

The alternative approach is to condense the twin constraints into a single parameter, Δ', by normalizing the basic vector of separation between the breakpoints, Δ. This second approach is more useful as the resulting analysis procedure retains its similarity to the basic breakpoint separation approach.

A procedure for normalizing the separation of the breakpoints can be developed by identifying a transformation capable of fixing the position of one breakpoint in the complex plane. The impact of the connection of a "new" generator on many aspects of network fault behavior can be expressed in a form similar to a transfer function, such as

$$\frac{\text{Fault parameter}}{\text{Fault parameter}(Z_G=\infty^{+})} = \left(\frac{Z_G - zero}{Z_G - pole}\right). \quad (13)$$

"Fault parameter $(Z_G = \infty+)$" is the comparative fault behavior of the original network to which the "new" generator is connected. It is possible to re-write (13) into a more useful form according to

$$\left(\frac{Z_G - zero}{Z_G - pole}\right) = \left(\frac{Z_G - zero}{Z_G - pole}\right) \times \frac{\frac{1}{pole}}{\frac{1}{pole}} = \left(\frac{\frac{Z_G}{pole} - \frac{zero}{pole}}{\frac{Z_G}{pole} - 1}\right). \quad (14)$$

This modification represents a complex mapping process that rotates and scales the complex impedance plane so that the location of the pole is always fixed at (1, 0) in the new domain. This ensures that the separation of the breakpoints in the mapped domain is given by

$$\Delta' = 1 - \frac{zero}{pole} = \frac{pole - zero}{pole} = \frac{\Delta}{pole}. \quad (15)$$

The separation of breakpoints outlined in (15) takes into account both the relative proximity of the breakpoints to the origin of the complex impedance plane as well as their separation. This overcomes the shortcomings of the basic breakpoint separation approach when generator designs are restricted. It allows a more general application of the breakpoint separation approach.

The normalized separation of breakpoints, Δ', is a vector quantity indicating the potential influence that the "new" generator could have on the fault behavior of the existing network. This parameter does not correspond directly to potential changes in physical fault parameters. Nevertheless, it can be manipulated to provide an estimate of the maximum proportional and/or absolute variation in the fault parameters resulting from the connection of the "new" generator. It also can be used to characterize the manner in which the "new" generator will affect fault behavior.

1) Absolute Variation in Fault Parameters: A feature of the mapping process used to normalize breakpoint separation is that certain points are coincident in both the original and transformed complex planes. The position of the origin of the complex plane and the point at infinity both remain unaffected by the normalization process. Knowledge of the fault behavior produced by these key generator designs can be used to estimate the maximum proportional variation in a fault parameter that could result from generator design changes.

This process can be illustrated by considering the connection of a "new" generator with very small equivalent impedance. By substituting $\mathrm{Z_G} = 0$ into (14) the fault behavior of the network containing the "new" generator can be expressed as a proportion of the fault behavior of the original system. This relationship is illustrated in (16)

$$\frac{\text{Fault parameter}(Z_G = 0)}{\text{Fault parameter}(Z_G = \infty^+)} = \left(\frac{\frac{0}{pole} - \frac{zero}{pole}}{\frac{0}{pole} - 1}\right) = \frac{zero}{pole} = 1 - \Delta'. \quad (16)$$

The numerical result of (16) is more useful than the value of the normalized breakpoint separation as it provides a direct estimate of the maximum potential variation in fault behavior that could result from the connection of the "new" generator. This allows the identification of fault conditions where generator design changes are likely to have a large impact.

Equation (16) demonstrates how the maximum potential variation can be related to the normalized separation of breakpoints. This is another example of the limits imposed by system configuration on the ability of changes to the design of a single generator to modify fault behavior. Again, the limits are readily expressed in terms of the separation of breakpoints.

Assessment of only the proportional variation of a fault parameter may not always be appropriate. Direct estimation of the potential absolute variation in fault behavior is sometimes more informative and can also be derived from the normalized separation of breakpoints. Equation (16) outlines the proportional relationship between the value of a fault parameter produced by a "new" generator with negligible impedance, i.e., $\mathrm{Fault\ parameter}(\mathrm{Z_G} = 0)$, and the behavior of the original system, i.e., $\mathrm{Fault\ parameter}(\mathrm{Z_G} = \infty^+)$. From this, the absolute variation in fault behavior can be expressed as

$$\text{Fault parameter}(Z_G = 0^+) - \text{Fault parameter}(Z_G = \infty^+) = -\Delta' \text{Fault parameter}(Z_G = \infty^+). \quad (17)$$

This is an estimate of the maximum absolute change in fault behavior resulting from the "new" generator. It will be more useful than the maximum proportional change, especially when addressing fault voltages.

2) Identification of Problematic Fault Conditions: A feature of (16) is that it provides an estimate of the maximum possible change to fault behavior resulting from the connection of a "new" physically realisable generator. It is important to realize that the normalized separation of breakpoints, Δ', is a vector quantity. One must consider not only the magnitude, $|\Delta'|$ but also the direction of separation between these normalized breakpoints, defined by $\theta_{\Delta'}$. Consequently, (16) defines not a single relationship, but a family of different relationships between the possible impact of the connection of a "new" generator and the configuration of the network to which it is connected. These multiple relationships are illustrated in Fig. 9.

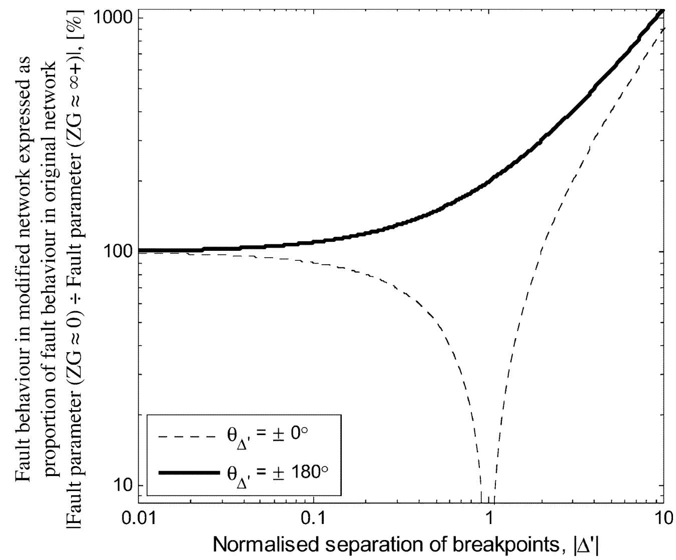

Fig. 9. Relationships between magnitude of normalized separation of breakpoints, $|\Delta'|$, and limits to proportional variation of fault parameter.

Fig. 9 compares a range of different magnitudes of the normalized separation of breakpoints, $|\Delta'|$, and the corresponding maximum potential variation in fault behavior produced by the addition of a "new" generator, calculated using (16), for two extreme cases of $\theta_{\Delta'}$. The magnitude of the normalized separation of breakpoints, $|\Delta'|$, can be thought of as summarizing the configuration of this remaining network. As a consequence, Fig. 9 provides an alternative way of visualizing the limitation imposed by the configuration of the remaining network on the ability of the "new" generator to modify fault behavior.

Several observations can be drawn from the results presented in Fig. 9. Firstly, Fig. 9 illustrates the significance of the comparative location of the respective breakpoints and the type of impact that the connection of the "new" generator will have on fault behavior. It is apparent that for fault incidents in which the argument of the normalized separation of the breakpoints, $\theta_{\Delta'}$, is around 0°, the connection of the "new" generator may be capable of producing a significant reduction in the relevant fault behavior. In contrast, for fault incidents for which $\theta_{\Delta'}$, is around 180°, the connection of the "new" generator appears capable of producing only various degrees of increase to the relevant fault behavior. This suggests that the argument of the normalized separation of the breakpoints, $\theta_{\Delta'}$, is an indicator of the manner in which the "new" generator can alter fault behavior.

Accordingly, Fig. 9 can also be used to identify problematic fault incidents. The impact of realistic changes to generator design will be confined by the bounds in potential fault variation shown in Fig. 9. By providing limits to both the maximum possible change to fault behavior and also illustrating the different types of fault behavior changes it is possible to highlight problematic fault conditions. Actual changes in fault behavior will still depend on the precise parameter values of the generator design selected. The normalized separation of breakpoints though provides a means by which potentially deleterious changes to

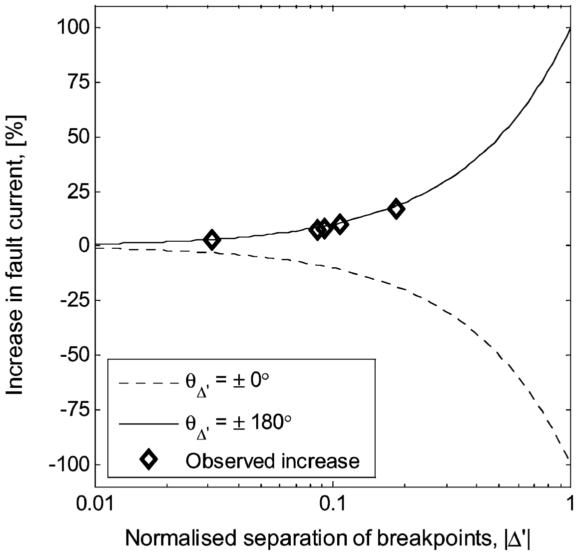

Fig. 10. Comparison of observed variation in fault currents in six-bus network to limits to potential variation extracted from breakpoint separation.

fault behavior can be identified before a possible generator modification.

The effectiveness of this representation is demonstrated by re-examining the fault behavior of the six-bus test system used in Section IV-B. Fig. 7 shows the increase in fault current produced by faults throughout the network, which results from a significant reduction in the sub-transient impedance of the generator connected at bus 2. In Fig. 10, this observed increase in fault current is plotted against, $|\Delta'|$, the magnitude of the normalized separation between the corresponding breakpoints. Finally, Fig. 10 also shows the bounds to potential change in fault behavior, which can be determined from (16), that correspond to each different value of $|\Delta'|$.

It is clear that the observed change in fault behavior is similar to but still bounded by the limits determined from the normalized separation of breakpoints. This suggests that from a knowledge of network configuration only, the likely impact of a physically realisable generator design change can be determined. Again, this process is simplified by the identification of breakpoints in the complex impedance plane.

VI. CONCLUSIONS

This paper has presented the development and significance of an analytical technique, termed the "breakpoint separation approach". The "breakpoint separation approach" represents a framework for understanding the relationship between generator design and network fault behavior. By expressing this relationship as a series of analytical functions, each with a similar format to a transfer function, it is possible to see clearly how the generator is attempting to modify the fault behavior of an existing system.

The configuration of the network, however, will limit the ability of the "new" generator to affect fault behavior. These limits can be extracted from the algebraic representation of the relationship between generator design and fault behavior and are summarized by "breakpoints" in the complex impedance plane. The location of breakpoints defines critical generator designs which lead to pronounced changes in fault behavior. The separation of the breakpoints provides a measure of the sensitivity of different fault conditions to generator design selection. Most importantly, the breakpoints can be determined using succinct algebraic expressions. This means that the range of techniques presented in this paper, which make up the "breakpoint separation approach", can be applied with equal ease to both different fault conditions and different network configurations.

Only limited numerical verification of the "breakpoint separation approach" is provided in the paper. Comprehensive verification of the approach will be provided in a future paper where the approach will be used extensively to characterize the impact of replacement of a conventional generator with Powerformer. The results will both establish the performance of this innovative generator and confirm the effectiveness of the "breakpoint separation approach".

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