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Novel adaptation of the critical clearing angle formula for faults on a three phase and a six phase line

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Abstract

Enhanced power transfer through polyphase conversion of a transmission line, specially three to six phase, as an alternative to upgrading the conventional three phase power transmission voltage is becoming an area of growing interest in the power industry. Among others this conversion will have an impact on the system stability. While the well-known symmetrical component method has been found suitable in modelling the unsymmetrical faults of a three phase system for transient stability analysis it appeared as difficult-to-apply for six phase system. In this paper a new technique has been proposed to determine the stability in terms of critical clearing angles for both three and six phase line faults. The method has been validated by applying it first for the faults on a 132 kV three phase double circuit line of a given practical power system and comparing the results with those obtained through the symmetrical component method. Then it has been applied for the faults on the same line but considered to have been converted into a 132 kV six phase single circuit line. The method, though an approximate one, is straightforward, simpler and faster than the symmetrical component method and provides sufficiently accurate results. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

A good deal of research effort applied since early 1970's has proved the economic viability of three to six phase conversion of an existing double circuit line. This requires using a phase conversion transformers at each end of the line but keeping unaltered the rights-of-way, tower and conductors of the three phase line and maintaining the same line to line voltage (as of the three phase line) between the adjacent conductors on the two vertical sides of the tower. However, further research is still underway regarding fault analysis [1–3], protection scheme [4] and stability aspects [5] of a six phase line embedded in the three phase grid system.

Critical clearing angle is an index of the transient stability limit which can be used for a large power network reducible [6–9] to a two-machine system connected by a transmission line. It is the highest permissible value of the relative swing between the rotors of two synchronous machines such that if a fault occurring on the line is cleared at or before this value the machines can be kept in synchronism.

The [5] appears to be the major one reported so far in the area of transient stability analysis for six phase line. In that work a six phase line between a three phase generator and an infinite bus was considered as two three-phase groups. It was assumed that the faults occurred on only one group although the conductors belonging to the group were not physically adjacent. This assumption helped the authors [5] in applying the three phase symmetrical component method [6] to calculate the critical clearing angles corresponding to the faults only between non-adjacent conductors though those do not occur in practice.

The works [1–3] though on fault currents and fault level computations, also show that the analyses of the

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common faults on adjacent conductors of a six phase line considering the phase conversion transformers are not amenable to the symmetrical component method.

In this paper a new approach has been proposed to compute the critical clearing angles for the unsymmetrical faults on both three and six phase lines. The method if desired can also be applied for symmetrical faults and for the faults involving non-adjacent conductors. The validation of the method has been done by comparing the critical clearing angles it gives for the three phase line with those achieved by applying the symmetrical component method on the three phase line.

2. The proposed approach

The critical clearing angle for a fault in a two-machine three phase system is found [6–9] using Eq. (1)

$$\delta_{cr} = \cos^{-1}\left[\frac{(\delta_{max} - \delta_0)\sin\delta_0 + r_2\cos\delta_{max} - r_1\cos\delta_0}{r_2 - r_1}\right]. \quad (1)$$

In Eq. (1) δ_0 is the pre-fault (initial) swing angle at which a power equal to P_m was being transferred between the two machines, and δ_{max} is maximum limit of swing angle after clearing the fault such that the two machines remain in synchronism. The quantity r_1 is the ratio of during-fault to pre-fault maximum transferable powers (P_{maxd}/P_{max}), and r_2 is the ratio of post-fault (i.e. after the fault is cleared) to pre-fault maximum transferable powers (P_{maxa}/P_{max}). It should be noted that $\delta_0 = \sin^{-1}(P_m/P_{max})$ and $\delta_{max} = \pi - \sin^{-1}(P_m/r_2P_{max})$.

In the symmetrical component method the ratios r_1 and r_2 are not computed directly in terms of power transferabilities rather are found in terms of the transfer reactances between two machines. These reactances are determined from the delta equivalent of the system model which combines one or more of the three sequence networks (positive, negative and zero) as appropriate for representing the fault type (symmetrical or unsymmetrical, shorted to ground or not), fault location, and system condition viz. pre-fault, during-fault and post-fault. But extension of Eq. (1) by the symmetrical component method for determining the critical clearing angles corresponding to the practical unsymmetrical faults involving adjacent conductors of a six phase line has been found difficult. This requires a new method which is described below. This method is also applicable for a three phase line.

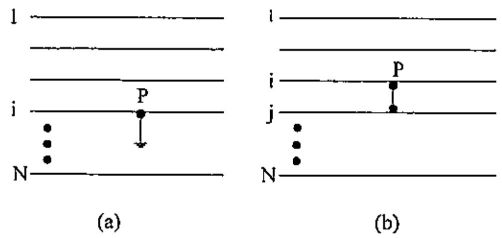

Fig. 1. An N conductor line with (a) L–G fault and (b) L–L fault.

The critical clearing angle formula has a justified [6–9] basis that the internal emfs behind the transient reactances of the two machines at two ends of a line remain constant. Also it is well-documented [6] that the mutual couplings between the conductors of a line are already taken into account while the per phase average inductance of the line is calculated. Using these two bases, the proposed method determines approximately the maximum power transferability through each conductor in any condition of the system independently of other conductors. However, there are some exceptional cases of faults where two or more conductors are considered together. The details is in what follows.

For an N conductor system, Eq. (2) is used to find the maximum power transferability P_{max_i} for each conductor ($i = 1$ to N) in the pre-fault condition. It should be noted that $N = 6$ for a three phase double circuit line (two conductors being electrically parallel in each phase) and a six phase single circuit line (one conductor per phase). In Eq. (2) $\bar{E}_{si}$ and $\bar{E}_{ri}$ are emf phasors, respectively at the sending and receiving end of the ith conductor while X_i is the net series reactance (including that of the conductor) between two emf sources.

$$P_{max_i} = \frac{|\bar{E}_{si}||\bar{E}_{ri}|}{X_i} \quad (2)$$

The during-fault maximum power transferability P_{maxd_i} through a conductor i is considered zero if the ith conductor either alone (Fig. 1a) or in combination with other conductors is shorted to the ground due to a fault. Eq. (3) shows this. If the ith conductor is involved in a symmetrical fault e.g. a three phase fault (L–L–L) on one circuit of a three phase line, then also Eq. (3) is applied. Because, the L–L–L fault is equivalent to the L–L–L–G for a three phase line.

$$P_{maxd_i} = 0 \quad (3)$$

If a fault shorts only two conductors (i and j) themselves but not to the ground as in Fig. 1(b) then the during-fault maximum power transferability $(P_{maxd})_{ij}$ through both the faulted conductors is determined together. For this instead of Eq. (3), Eq. (4) is used in conjunction with the L–L fault model of Fig. 2 and its simpler equivalent of Fig. 3. The subscripts 1 and 2 in Figs. 2 and 3, denote conductors i and j, respectively. The quantities in Eq. (4) have similar significance as those in Eq. (2) excepting X. The total reactance in each conductor (i or j) between the sending end source point and the fault point on the line is X_s. The total reactance in each conductor between the fault point and the receiving end source point is X_r.

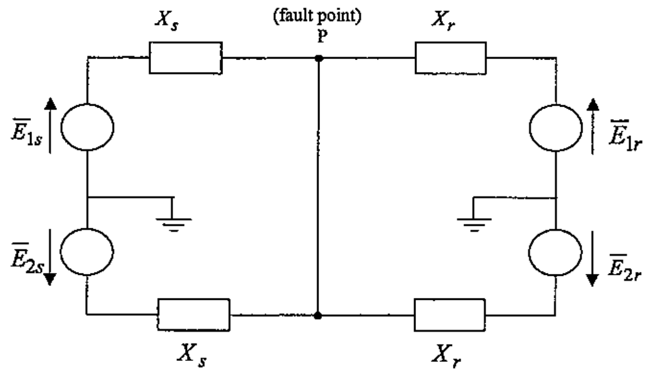

Fig. 2. Modelling of a L–L fault.

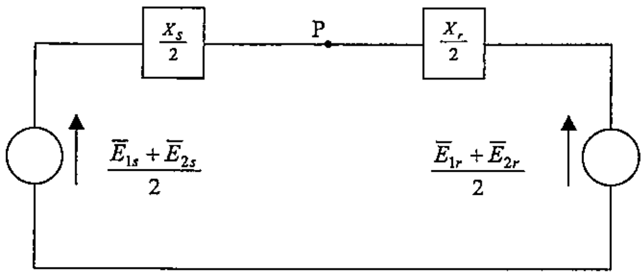

Fig. 3. Simplification of the model of Fig. 2.

$$(P_{\text{maxd}})_{ij} = \frac{\dfrac{|\bar{E}_{si}+\bar{E}_{sj}|}{2}\dfrac{|\bar{E}_{ri}+\bar{E}_{rj}|}{2}}{\left(\dfrac{X_s+X_r}{2}\right)} \quad (4)$$

It should be noted that if a fault shorts three conductors (i, j, and k) themselves but not to the ground (e.g. an L–L–L fault on one side of the six phase line) then also Eq. (4) can be extended with the addition of the terms $\bar{E}_{sk}$ and $\bar{E}_{rk}$ and division by three instead of two.

The during-fault maximum power transferability P_{maxd_i} through a conductor i which is not faulted is determined using Eq. (5).

$$P_{\text{maxd}_i} = \frac{|\bar{E}_{si}||\bar{E}_{ri}|}{X_i} \quad (5)$$

The post-fault maximum power transferability P_{maxa_i} is found using Eq. (6) if the ith conductor is involved in any type of fault or is tripped by fault clearing. On the contrary, Eq. (7) is used if the ith conductor is not involved in any fault and remains energized after clearing the fault.

$$P_{\text{maxa}_i} = 0 \quad (6)$$

$$P_{\text{maxa}_i} = \frac{|\bar{E}_{si}||\bar{E}_{ri}|}{X_i} \quad (7)$$

It should be noted that the right sides of Eq. (2), Eq. (5) and Eq. (7) are same for an unfaulted conductor in all the three conditions (pre-fault, during-fault and post-fault).

The power transferabilities through each individual (or group of) conductor(s) obtained thus under respective system condition are then added together to calculate the ratios r_1 and r_2 as in Eq. (8) and Eq. (9).

$$r_1 = \frac{\sum_{i=1}^{N} P_{\text{maxd}_i}}{\sum_{i=1}^{N} P_{\text{max}_i}} \quad (8)$$

$$r_2 = \frac{\sum_{i=1}^{N} P_{\text{maxa}_i}}{\sum_{i=1}^{N} P_{\text{max}_i}} \quad (9)$$

The values of r_1 and r_2 from Eq. (8) and Eq. (9) are substituted in Eq. (1) to obtain the critical clearing angle for the corresponding fault.

The proposed method differs from the symmetrical component method mainly in three respects viz. (i) the ratios r_1 and r_2 are determined in terms of maximum power transferabilities rather than using transfer reactances, (ii) the power transferabilities are computed in this method using only the given model i.e. the positive sequence network of the system and (iii) the unfaulted phases are treated independently without the use of any transformation matrix.

As further support of the proposed method's basis it can be reemphasized that since the internal emfs of a synchronous machine are only of positive sequence and since no power results from the combination of positive sequence voltages with negative sequence or zero sequence currents, the generated power of a synchronous machine and the synchronizing power between the various synchronous machines of a system are only [9] positive sequence power. Therefore the positive sequence network is of primary interest in a stability study, and the zero and negative sequence networks are only of secondary interest. Furthermore, the mutual coupling is already included [6] in the per phase reactance calculation and does not need reconsideration. Moreover, a quantitative validation and accuracy of the method can be judged by the results which follow in Section 4.

3. System studied

An important three phase double circuit line of Bangladesh Power Development Board grid (BPDB) system has been considered as an example to illustrate the proposed method. The line is between Ghorasal and Ishurdi buses and interconnects two zones of the system. Fig. 4 and Fig. 5 respectively shows the models of the line as a 132 kV double circuit line and as that when converted into a 132 kV single circuit six phase line.

It should be noted that in the Fig. 4 and Fig. 5 the three phase power system in which the line is embedded has been represented [6,9] by two Thevenin's emfs E_{thg} and E_{thi} in series with the corresponding Thevenin's reactances X_{thg} and X_{thi} respectively and 132 kV Ghorasal and Ishurdi buses. The Thevenin's parameters were obtained from BPDB supplied fault MVA and fault current data for the two buses.

The line reactance in six phase mode has been calculated using the same method [6] as the one used in the three phase mode. Each phase conversion transformer between three and six phase buses in Fig. 5 is a bank of three single phase transformers each rated 75 MVA and $(132/\sqrt{3})/264$ kV with the HT winding grounded at the centre points so that 132 kV would appear between each HT terminal and the centre point and with an equivalent reactance of 13% between the LT and each half of the HT winding.

Table 1 provides the line reactances (in three and six phase modes), reactance of each phase conversion transformer and the Thevenin's parameters in per unit of chosen base values. The Thevenin's and line reactances shown for the 132 kV three phase double circuit model represent both positive and negative sequence values while their zero sequence values are respectively 0.024, 0.091 and 0.6355 p.u. The three sequence reactance values are required in the symmetrical component method.

The number of phases on the high tension side of the phase conversion transformer in Fig. 5 is six respectively denoted by a, f, e, b, c, d when conductors of phases a, f, e are adjacent on the one side of the line while conductors of phases b, c, d are adjacent on the other side such that the voltage between adjacent conductors is 132 kV and that between the non-adjacent conductors

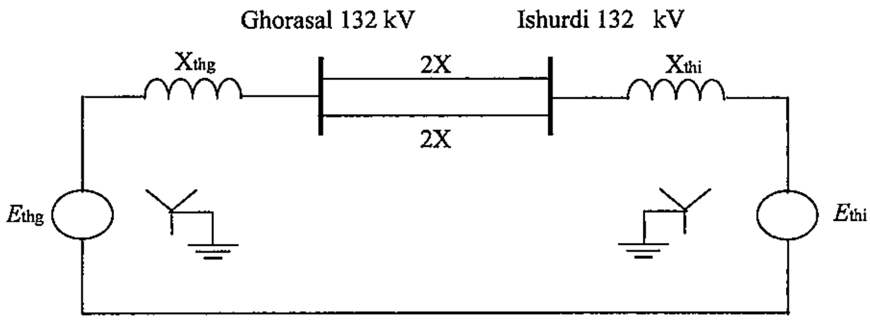

Fig. 4. Model for the 3-ϕ double circuit line between 132 kV Ghorasal and Ishurdi buses of the BPDB network.

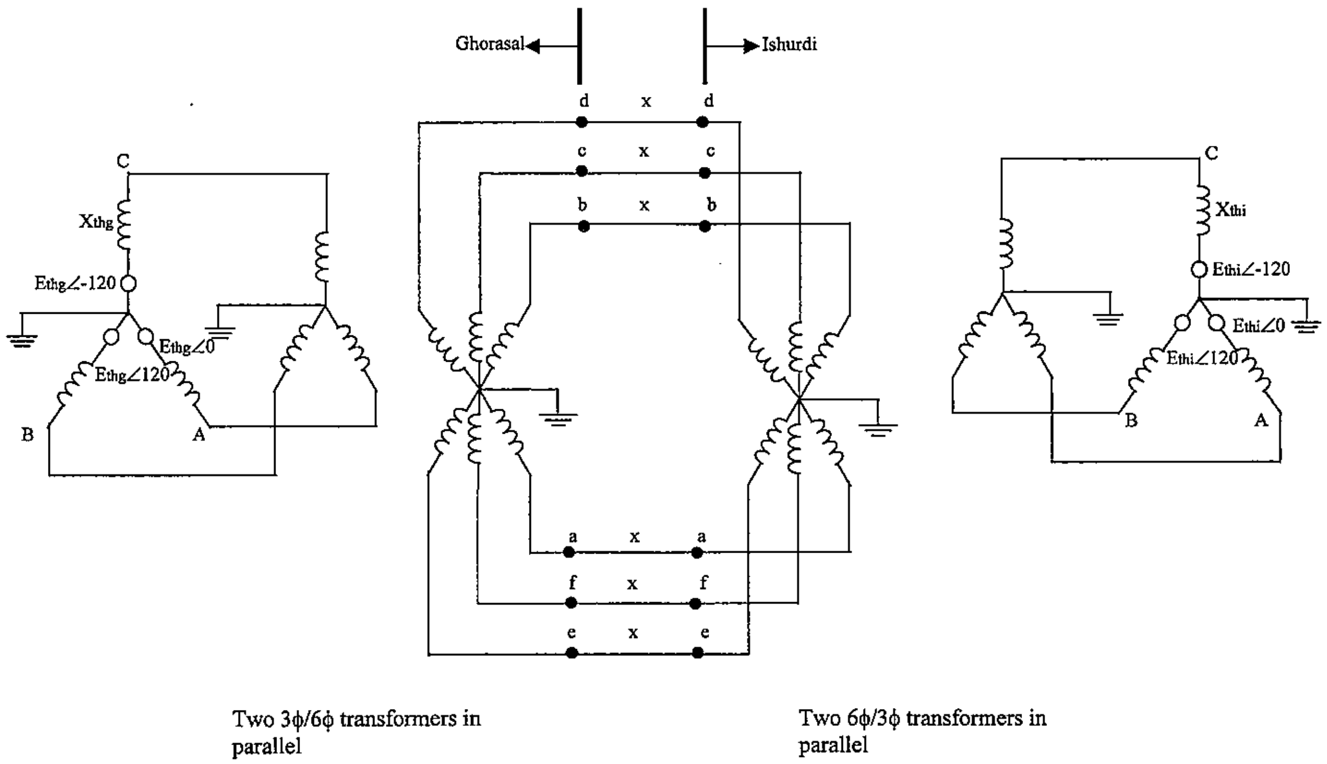

Fig. 5. Model for 132 kV six phase single circuit conversion.

Table 1
Three and six phase line model parameters

Parameters	132 kV three phase double circuit line	132 kV six phase single circuit line
Base voltage (line to line)	132 kV	132 kV (3-phase side of transformer)
		$132\times\sqrt{3}$ kV (6-phase side)
Base MVA	100 MVA	100 MVA
Thevenin's parameters in per unit	$E_{thg}=1.01$, $E_{thi}=1.0$	$E_{thg}=1.01$, $E_{thi}=1.0$
	$X_{thg}=0.036$, $X_{thi}=0.069$	$X_{thg}=0.036$, $X_{thi}=0.069$
Reactances	Line: $x=0.2542$ p.u./phase	Line: $x=0.1685$ p.u./phase; each phase conversion transformer: $x_t=0.058$ p.u./phase

is $132\times\sqrt{3}$ kV. Due to this the line to line base kV on the HT (six phase) side of the phase conversion transformer has been selected as $132\times\sqrt{3}$ kV in Table 1.

4. Results and discussions

The line under study with the two Thevenin's sources respectively at Ghorasal and Ishurdi buses as shown in Figs. 4 and 5 has been considered as a two-machine system. The Thevenin's reactances X_{thg}, X_{thi} and emfs E_{thg}, E_{thi} have been taken as respectively the transient reactances and constant internal emfs behind the transient reactances of the two machines. Also it has been considered for both the symmetrical component and the proposed methods that various types of faults occur on the line at the worst point i.e. very close to the sending end bus at Ghorasal and a power of $P_m=1.0$ p.u. was being supplied through the line from Ghorasal to Ishurdi before occurrence of the faults.

It should be noted that for any type of fault on a three phase double-circuit line it is the practice [6] to clear the fault by opening the breakers at both ends of the whole circuit containing the faulted conductor(s) so that in the post-fault condition only three phases (conductors) of the unfaulted circuit remain energized. To be in line with this, it has been considered that for any fault on the adjacent conductors of one side in the six phase single circuit line the fault is cleared by opening the breakers at both ends of all the phases (conductors) of the faulted side. However, it is worth noting that unlike the symmetrical component method the proposed method can also be applied even in the case a fault is cleared by opening only the faulted conductor(s) instead of the whole circuit/all the phase(s) on the faulted side.

4.1. Symmetrical component method applied for the three phase line

Table 2 shows the critical clearing angles obtained by applying the symmetrical component method for the symmetrical (L–L–L) as well as unsymmetrical faults on the three phase line. The initial swing angle δ_0 in the pre-fault condition of the considered three phase line was 20.84°. In Table 2 the term 'line' (i.e. notation 'L') denotes a particular conductor of a phase while 'G' denotes ground.

It can be seen in this Table 2 that for two of the unsymmetrical faults on the three phase line the system is inherently stable (I.S.) i.e. remains stable even if the fault is not cleared. This arises only when the given operating conditions (voltages) and line parameters are such that the maximum power transferability during the fault (P_{maxd}) is sufficiently greater [9] than the prefault power being supplied over the line (P_m) so that a decelerating power acts to limit the inter machine oscillations. The cases of inherent stability are identified by the value of δ_{cr} from Eq. (1) which becomes indeterminate i.e. cos δ_{cr} is outside the range of ± 1.

4.2. Proposed method applied for the three phase line

As explained in Section 2, application of the proposed method for various faults on the three phase line is straightforward requiring computation of the power transferability ratios r_1 and r_2 using only the positive sequence data which are all given in Table 1.

Table 2
Critical clearing angles for the three phase double circuit line by symmetrical component method

Types of faults	Faulted phases	Critical clearing angle in elect. degrees
Line-to-ground (L–G)	a–G	Inherently stable
Line-to-line (L–L)	a–b	Inherently stable
Double line-to-ground (L–L–G)	a–b–G	86.99°
Three phase (L–L–L)	a–b–c	59.83°

Table 3
Critical clearing angles for the three phase double circuit line by the proposed method

Types of faults	Faulted phases	Input power P_m in p.u.	Pre-fault maximum power P_{max} in p.u.	$r_1 = \Sigma P_{maxd}/\Sigma P_{max}$	$r_2 = \Sigma P_{maxa}/\Sigma P_{max}$	Critical clearing angle δ_{cr} in elect. degrees
L–G	a–G	1.0	2.81	0.666	0.586	Inherently stable
L–L	a–b	1.0	2.81	0.500	0.586	Inherently stable
L–L–G	a–b–G	1.0	2.81	0.333	0.586	94.14°
L–L–L	a–b–c	1.0	2.81	0.000	0.586	59.83°

For a three phase line only the L–L fault does not involve ground and the during-fault power transferability through the faulted phases ('a' and 'b' as considered in Table 2) is computed together considering the model of Fig. 2. E_{1s} and E_{1r} in Fig. 2 are respectively the phasor values of sending end and receiving end source emfs (which are indeed the two Thevenin's emfs E_{thg} and E_{thi}) in phase 'a' of the faulted phases. Similar significance holds good for E_{2s} and E_{2r} in phase 'b'. X_s is the total reactance in each phase between the sending end source point and the fault point P (close to the sending end bus) on the line. X_r is the total reactance in each phase between the fault point and the receiving end source point. Each of the two emf sources along with their respective reactance in series on either side of the fault point P can be converted into a current source with a parallel susceptance reciprocal of the corresponding reactance. Finally, these two pairs of current sources together with their parallel susceptances have been reconverted respectively into two single emf sources with two corresponding series reactances as in Fig. 3 from which the power transferability through the faulted phases a–b $(P_{maxd})_{ab}$ is computed and added with the during-fault power transferability limit $(P_{maxd})_c$ of the unfaulted phase 'c' in a straightforward manner.

It should be noted that in determining during-fault power transferability, each conductor of the unfaulted side (circuit) of the three phase double circuit line is required to be considered together with the electrically parallel conductor in the corresponding phases of the faulted side (circuit) due to the location of the fault at almost the sending end bus.

Table 3 provides the critical clearing angles for the various faults on the considered three phase line determined from Eq. (1) after computing the ratios r_1 and r_2 by the proposed method.

A comparison of the critical clearing angles computed by the symmetrical component method (Table 2) and by the proposed method (Table 3) for the same faults on the three phase double circuit line shows that they are the same excepting for the L–L–G fault. It should be noted that the way r_1 and r_2 are calculated in the proposed method gives slightly different r_1 from those by the symmetrical component method only for two faults on a three phase double circuit line e.g. the L–G and the L–L–G fault. The values of r_1 for these two faults on the considered line are respectively 0.666 and 0.333 (by the proposed method) as against 0.632 and 0.294 (by the symmetrical component method). However, the system is found inherently stable for the L–G fault by both the methods while for the L–L–G fault the critical clearing angles differ only by (94.14 − 86.99° =) 7.15° or 0.12 radians which is acceptable.

4.3. Proposed method applied for the six phase line

The 132 kV six phase single circuit model of Fig. 5 for the considered line has been redrawn in Fig. 6 in the form of an equivalent circuit referred to the high tension i.e. six phase side of the phase conversion transformer. The Thevenin's emf sources shown in Fig. 6 have relative phase angles 0, − 60, − 120, − 180, − 240 and −300° respectively for the phases a, f, e, d, c and b. Among these phases a, f, e are adjacent on one side while b, c, d are adjacent on the other side of the line as mentioned in Section 3. The per unit values of the Thevenin's, transformer and line reactances have not been marked explicitly for each phase of the model in Fig. 6 just to avoid cluttering of too many numbers. These parameters' values are as in Table 1.

Though the proposed method can be applied for all the faults involving adjacent or non-adjacent conductors of a six phase line the main emphasis in the limited space of the paper has been put on analysing stability corresponding to the practical and common faults which are all unsymmetrical and involve only the adjacent conductors. For a six phase single circuit line these faults are of the types L–G, L–L, L–L–G, L–L–L and L–L–L–G. Since the phase difference between adjacent phases a and f is − 60° and that between other adjacent pair a and e is − 120° the L–L fault has two combinations viz. a–e and a–f and likewise the L–L–G fault has two combinations viz. a–e–G and a–f–G.

The way the proposed method is applied for critical clearing angles for the six phase line corresponding to the L–G and L–L, and L–L–G faults at a point P close to its sending end is similar to that for respectively the L–G, L–L and L–L–G faults on the three phase line as described in Section 4.2. Moreover, the L–L–L–G fault on the six phase line is also treated in a way similar to that for the L–L–G fault on the three phase line.

The L–L–L fault on the six phase line which is not symmetrical and does not involve ground requires the same treatment as the L–L fault in three phase system excepting that in calculating the total during-fault power transferability through all the faulted phases (a–f–e), the models of Figs. 2 and 3 can be used with only the addition of a third pair of emfs and reactances corresponding to phase ‘e’. Each of the three emf sources along with respective reactance in series on either side of the fault point P, can be converted into a current source with a parallel susceptance reciprocal of the corresponding reactance. Finally, these two groups of three current sources together with their parallel susceptances can be reconverted into two single emf sources each with a corresponding series reactance.

Table 4 provides the critical clearing angles for various faults occurring at a point close to the sending end of the considered six phase line determined from Eq. (1) after computing the ratios r_1 and r_2 by the proposed method.

In Table 4 it should be noted that for all the unsymmetrical faults considered in this paper for the six phase line, the maximum power transferable during fault i.e. r_1 P_{max} was sufficiently grater than the mechanical power input P_m so that a retarding force acted to prevent loss of synchronism and stability, and the system remained inherently stable for sustained fault conditions i.e. even if the faults were not cleared.

It should be noted that whether a given system will be inherently stable depends upon the types of faults and hence the number of affected (faulted) phases or conductors, and the system operating voltages and parameters. For example, the system with the three phase line was also found inherently stable by both the methods i.e. the symmetrical component method and

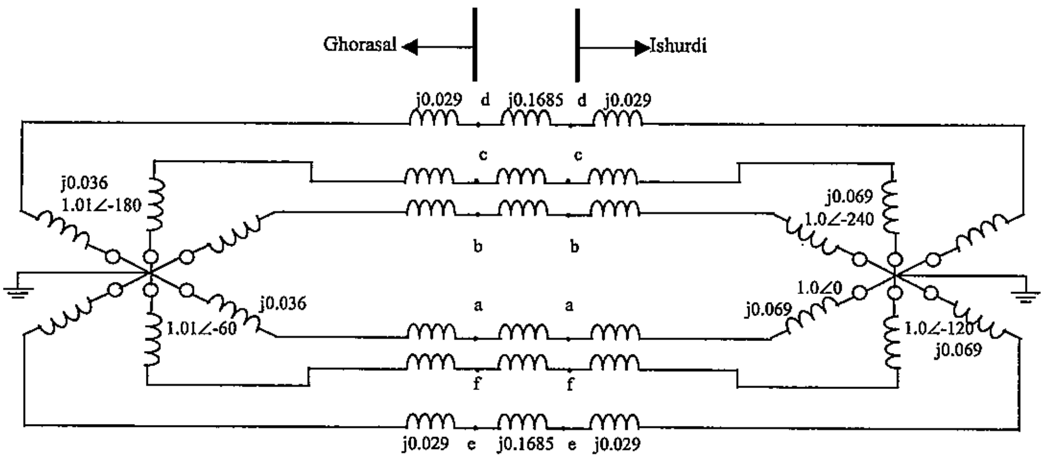

Fig. 6. Representation of the model of Fig. 5 with reference to the six phase (high tension) side of the phase conversion transformer.

Table 4
Critical clearing angles for the six phase single circuit line by the proposed method

Types of faults	Faulted phases	Input power P_m in p.u.	Pre-fault maximum power P_{max} in p.u.	$r_1 = \Sigma P_{maxd}/\Sigma P_{max}$	$r_2 = \Sigma P_{maxa}/\Sigma P_{max}$	Critical clearing angle δ_{cr} in elect. degrees
L–G	a–G	1.0	3.04	0.833	0.500	Inherently stable
L–L	(i)a–f	1.0	3.04	0.915	0.500	Inherently stable
	(ii)a–e	1.0	3.04	0.750	0.500	
L–L–G	(i)a–f–G	1.0	3.04	0.666	0.500	Inherently stable
	(ii)a–e–G	1.0	3.04	0.666	0.500	
L–L–L–G	a–f–e–G	1.0	3.04	0.500	0.500	Inherently stable
L–L–L	a–f–e	1.0	3.04	0.723	0.500	Inherently stable

the proposed method for two of the unsymmetrical faults as may be seen in Tables 2 and 3. However, for a line with different parameters the critical clearing angles may have finite numerical values instead of inherent stability margin for the same types of faults as considered here. As there were readily available data on fault level at the two ends of the line considered here, the example in this paper has been presented with respect to this line.

5. Conclusions

In this paper a novel approach has been proposed for determining the critical clearing angles and hence the transient stability for both three and six phase line faults. The proposed method is applicable for any type of fault (symmetrical or unsymmetrical) at any location involving adjacent or non-adjacent conductors of both three phase and six phase lines and for fault clearing either by opening all the conductors of the faulted side as is the practice or by opening only the faulted conductors i.e. selective tripping. However, in the limited space of the paper the method has been illustrated for only the practical and common faults involving adjacent conductors at the worst location on both three and six phase lines considering the usual practice of fault clearing. The examples represent a specific 132 kV three phase double circuit line of a practical and realistic power system and the same considered to have been converted into a 132 kV six phase single circuit line.

The method has been validated by the values of the critical clearing angles it provided for the various faults on the three phase line. These are either the same or of same accuracy as those obtained by the symmetrical component method applied to the same three phase line for the same faults.

The proposed method, though an approximate one, provides sufficiently accurate results and is applicable for a line of any number of phases. Moreover, this method is straightforward, simpler and faster than the symmetrical component method which is suitable only for a three phase line.

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