小形電子計算機에 의한 大電力系統의 故障解析

논 문
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Analysis of Faults of Large Power System by Memory-Limited Computer

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Abstract

This paper describes a new approach for minimizing working memory spaces without loosing too much amount of computing time in the analysis of power system faults. This approach requires the decomposition of large power system into several small groups of subsystems, forms individual bus impedance matrices, store them in the auxiliary memory, later assembles them to the original total system by algorithms. And also the approach uses techniques for diagonalizing primitive impedances and expanding the system bus impedance matrices by adding a fault bus. These scheme ensures a remarkable savings of working storage and continous computations of fault currents and voltages with the voried fault locations.

INTRODUCTION

In general, computer methods in power system analysis are hampered by the space limitation of the primary memory. This paper aims to suggest a new approach for minimizing memory spaces without sacrificing computing time too much in the analysis of power system faults.

In the frist application of digital computers to fault calculation, the bus frame of reference in admittance form was employed and required a complete iterative solution for each fault type and location. The procedure was time-consuming, and so this method was not adopted generally[2]

The development of techniques for applying a digital computer to form the bus impedance matrix made it feasible to use Thevinin's theorem for fault calculations. This approach provided an efficient means of determining fault currents and voltages because these values can be obtained with few arithmetic operations involving only related portions of the bus impedance matrix [2]

The methods of forming the bus impedance matrix can be, generally, classified in one of two categories—the one being the incidence matrix method by the concept of network topology [2,3] and the other the bus impedance matrix successive formation method by the algorithms proposed by Brown, Person, Kirchmayer, Stagg and El-Abiad [1].

The former method is theoretically elegant but the transformation and inversion of complex network matrices for a large scale power system require bulky amounts of two-dimensional array in the memory as well as inevitable error accumulation and lengthy computational time

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resulting from inversion of large size matrices. The latter method adding one element at a time still cannot be relieved from a disadvantage of requiring large memory spaces although the computational time is remarkably reduced.

In this paper a new approach is undertaken for improving the conventional methods above, and is based on the following underlying principles:

1. The primitive admittance matrix of the power system is diagonalized and converted to the one-dimensional primitive admittance vector with the use of the equivalent circuit conversion, thus reducing remarkable amounts of memory spaces.

2. Instead of forming the bus impedance matrix of the entire power system, the power system is partitioned into appropriate number of subsystem groups, and for each separate subsystem the respective bus impedance matrix is computed and stored permanently in the auxiliary storage. This scheme also makes great contributions to memory savings, computing time reduction and error minimization.

3. In the steps of determing the fault currents and voltages, the only required portions of bus impedances for the entire system are computed and temporarily stored instead of evaluating all of the bus impedances by the algorithms suggested in this paper. This scheme ensures a remarkable curtailment of computational time.

4. The determination of fault currents are classified into two categories. That is, the currents in the line elements where the fault has occurred and the elements magnetically coupled with them are computed on a single-circuit-line basis. Those in other elements required are computed on a double-circuit-line basis if the elements belong to double-circuit-lines.

FORMATION OF PRIMITIVE ADMITTANCE VECTORS

The primitive impedance matrix $Z^{a,b,c}$ of the three-phase network can be subdivided into $m\times m$ numbers of square submatrices of 3 dimension where m is the numbers of three-phase line elements, and the submatrix $z^{a,b,c}_{pq,rs}$ is represented by [2].

$$z^{a,b,c}_{pq,rs} \triangleq \begin{pmatrix} z^{a,a}_{pq,rs} & z^{a,b}_{pq,rs} & z^{a,c}_{pq,rs} \\ z^{b,a}_{pq,rs} & z^{b,b}_{pq,rs} & z^{b,c}_{pq,rs} \\ z^{c,a}_{pq,rs} & z^{c,b}_{pq,rs} & z^{c,c}_{pq,rs} \end{pmatrix} \quad (1)$$

where $z^{a,a}_{pq,rs} \triangleq$ self-impedance of phase a of the three-phase element connecting nodes p and q in the case that $p=r$ and $q=s$, mutual-impedance between phase a of the pq element and phase a of the rs element.

$z^{a,b}_{pq,rs} \triangleq$ mutual-impedance between phase a of the pq element and phase b of the rs element, and so forth.

In the balanced three-phase network characterized by

$$\left.\begin{aligned} z^{m0}_{pq,pq} &\triangleq z^{a,a}_{pq,pq} = z^{b,b}_{pq,pq} = z^{c,c}_{pq,pq} \\ z^{m1}_{pq,pq} &\triangleq z^{a,b}_{pq,pq} = z^{b,c}_{pq,pq} = z^{c,a}_{pq,pq} \\ z^{m2}_{pq,pq} &\triangleq z^{b,a}_{pq,pq} = z^{c,b}_{pq,pq} = z^{a,c}_{pq,pq} \\ z^{m}_{pq,rs} &\triangleq z^{a,b}_{pq,rs} = z^{b,c}_{pq,rs} = z^{c,a}_{pq,rs} = z^{b,a}_{pq,rs} = z^{c,b}_{pq,rs} \\ &= z^{a,c}_{pq,rs} = z^{a,a}_{pq,rs} = z^{b,b}_{pq,rs} = z^{c,c}_{pq,rs} \end{aligned}\right\} \quad (2)$$

applying the symmetrical-component transformation matrix T_s defined by

$$T_s \triangleq \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \quad (3)$$

the submatrix $z^{a,b,c}_{pq,pq}$ or $z^{a,b,c}_{pq,rs}$ can be transformed into the diagonal submatrix $z^{0,1,2}_{pq,pq}$ or $z^{0,1,2}_{pq,rs}$ as follows:

$$z^{0,1,2}_{pq,pq} \triangleq (T_s{}^*)^t z^{a,b,c}_{pq,pq}\, T_s = \begin{pmatrix} z^0_{pq,pq} & 0 & 0 \\ 0 & z^1_{pq,pq} & 0 \\ 0 & 0 & z^2_{pq,pq} \end{pmatrix} \quad (4)$$

where $z^0_{pq,pq} \triangleq$ zero sequence primitive impdance of the pq element

$$= z^{m0}_{pq,pq} + z^{m1}_{pq,pq} + z^{m2}_{pq,pq}$$

$z^1_{pq,pq} \triangleq$ positive sequence primitive impedance of the pq element

$$= z^{m0}_{pq,pq} + a^2 z^{m1}_{pq,pq} + a\, z^{m2}_{pq,pq}$$

$z^2_{pq,pq} \triangleq$ negative sequence primitive impedance of the pq element

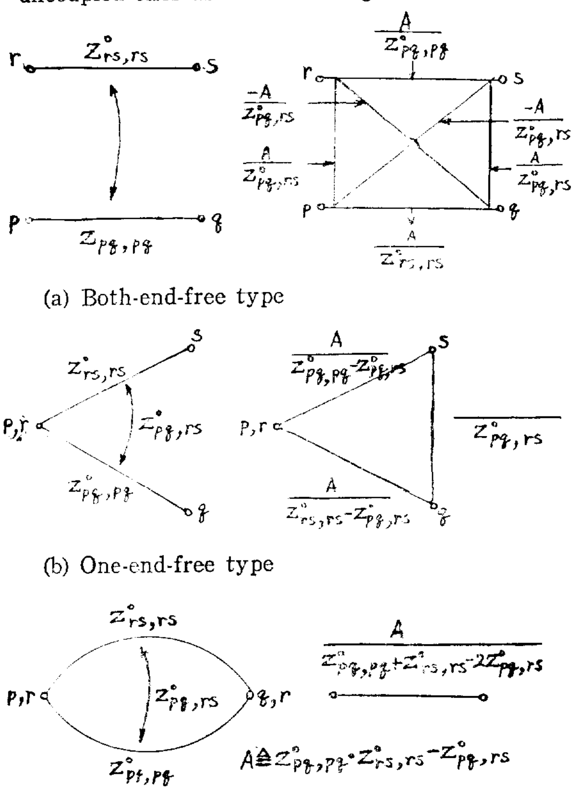
$$= z^{m0}_{pq,pq} + a\, z^{m1}_{pq,pq} + a^2\, z^{m2}_{pq,pq}$$

$$z^{0,1,2}_{pq,rs} \triangleq (T_s{}^*)^t \, z^{a,b,c}_{pq,rs} \, T = \begin{pmatrix} z^0_{pq,rs} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad (5)$$

whers $z^0_{pq,rs} \triangleq$ zero sequence mutual coupling (impedance) between the pq and rs elements $=3\ z^m_{pq,rs}$.

Noticing Eq. 5, it is seen that zero sequence mutual impedance $z^0_{pq,rs}$ still remains in the case of mutual coupling between adjacent circuit lines, particularly of double-circuit lines, although applying the symmetrical-component method, and so the primitive admittance matrix of three-phase network containing double-circuit lines can not be diagonalized.

In order to overcome these difficulties, the author pursues an equivalent circuit conversion technique which converts coupled circuits to uncoupled ones as shown in Fig. 1.



(a) Both-end-free type

(b) One-end-free type

(c) Both-end-connection type

Fig. 1. Conversions from coupled cricuits to uncoupled circuits.

This conversion scheme enables it to separate three-phase primitive impedance or admittance matrix to the respective positive-, negative-, and zero-sequence component matrices and then to diagonalize them to one-dimensional vector forms as follows:

$$\left.\begin{aligned} z^\alpha_{pq} &\triangleq z^\alpha_{pq,pq} = 1/y^\alpha_{pq} \\ z^\alpha_{pq,rs} &= 0, \quad y^\alpha_{pq,rs} = 0 \end{aligned}\right\} \qquad (6)$$

where $\alpha=1$ (positive sequence), 2 (negative sequence), 0 (zero sequence).

Thus, instead of the $z^{a,b,c}_{pq,rs}$ in Eq. 1, each sequence-component of the primitive admittance vectors y^α_{pq} can be independently computed by Eq. 6, inputting the z^α_{pq}, and stored.

FORMATION OF SEQUENCE BUS IMPEDANCE MATRICES

The respective sequence bus admittances $Y^0_{i,j}$, $Y^1_{i,j}$, $Y^2_{i,j}$ are computed as follows:

$$Y^\alpha_{i,j} = \sum_{pq=1}^{l} A^t_{pq,i}\ y^\alpha_{pq}\ A_{pq,j} \qquad (7)$$

$i, j=1, 2, \cdots\cdots\cdots\cdots m$ (bus number)

$\alpha=0, 1, 2$ (sequence component)

where m=total numbers of buses

l=total numbers of network elements

$A_{pq,i}$=element of bus incidence matrix

Therefore, the corresponding sequence bus impedances, $Z^0_{i,j}$, $Z^1_{i,j}$, $Z^2_{i,j}$ can be computed, inverting Y^0_{Bus}, Y^1_{Bus}, Y^2_{Bus}, the sequence bus admittance matrices whose element is represented by Eq. 7.

SEQUENCE BUS IMPEDANCE ASSEMBLING

Although the conversion from the primitive ad mittance matrices to the corresponding vectors has resulted in a remarkable savings of memory spaces, the sequence bus admittance matrices still require large amounts of memory. So, this paper suggests a system decomposition and assembling technique in this section.

For the application of the technique some definitions and algorithms have to be described as follows:

〔**Definition 1**〕 An total system is defined as an original system expressed in the bus impedance matrix of zero-, positive-, or negative-sequence component.

〔**Definition 2**〕 A subsystem is defined as an individual division of a total system such that the total system is decomposed into several divisions completely separated by disconnecting an appropriate line element or elements at bus or buses.

〔**Definition 3**〕 A partial system is defined as a portion of a total system connected by reconnecting a disconnected line element or elements.

〔**Definition 4**〕 An initial connection is defined as a connection by which two separate subsystems or one partial system and subsystem is initially connected.

〔**Definition 5**〕 A successive connection is defined as a connection by which an already connected partial system is successively connected between corresponding both buses.

〔**Definition 6**〕 An assembled system is defined as a set whose elements consist of partial system (s) and subsysem(s) to be collected for later connection (s).

〔**Algorithm 1**〕 If two systems (partial or sub) x, y, belonging to and assembled system, are mutually sperated without connection, the assembled system bus impedance $Z^A_{i,j}$ is expressed as

$$\left.\begin{aligned} &Z^A_{ix,jy}=Z^A_{iy,jx}=0 \\ &Z^A_{ix,jx}=Z_{ix,jx}, \quad Z^A_{iy,jy}=Z_{iy,jy} \end{aligned}\right\} \qquad (8)$$

where i_x, j_x and i_y, j_y=bus of system x and y

$Z_{ix,jx}$ and $Z_{iy,jy}$=bus impedance of system x and y.

〔**Algorithm 2**〕 If two systems are initially connected by reconnecting them between buses p_x and p_y, the $Z^A_{i,j}$ is expressed as

$$\left.\begin{aligned} &Z^A_{ix,jx}=Z_{ix,jx}-Z_{ix,px}\cdot Z_{px,jx}/(Z_{px,px}+Z_{py,py}) \\ &Z^A_{ix,jy}=Z_{ix,px}\ Z_{py,jy}/(Z_{px,px}+Z_{py,py}) \end{aligned}\right\} \qquad (9)$$

and either of p_x and p_y is degenerated.

〔**Algorithm 3**〕 If a partial system is successively connected by reconnecting them between buses p_r and p_s, the partial system bus impedance $Z^p_{i,j} \in Z^A_{i,j}$ is modified to $Z^{p'}_{i,j}$ as follows:

$$Z^{p'}_{i,j}=Z^p_{i,j}+\left(Z^p_{i,ps}-Z^p_{i,pr}\right)\left(Z^p_{pr,j}-Z^p_{ps,j}\right)\Big/\left(Z^p_{ps,ps}+Z^p_{pr,pr}-2Z^p_{pr,ps}\right) \qquad (10)$$

and either of p_r and p_s is degenerated.

Since an usual fault analysis is restricted to a particular line-element region adjacent to the fault location, it is enough to determine only a needed portion of but impedances for the region.

For the purpose of minimizing working memory spaces and curtailing computational time the total system is decomposed into appropriate several subsystems. Then the respective bus impedance matrix for each subsystem is indivisually computed by Eq. 7 and matrix inversion and stored on an auxiliary storage or card deck for later retrieval and assembly.

The assembling procedures are as follows:

1. All of only needed bus numbers and disconnected bus numbers are defined.

2. All of subsystems are sequentially numbered in assembling order.

3. At first, the first subsystem s_1 is retrieved and a new bus impedance matrix is formed in a particular area of the working storage for predifined buses and disconnected buses of the s_1

4. Next, the second subsystem s_2 is retrieved and the assembling proccess is carried out on the s_1 and s_2.

a) If both systems share no common disconnected but pair to be reconnected, the bus impedance matrix assembled for the s_1 and s_2 is formed, using the algorithm in Eq. 8, and then the process is shifted to the third subsystem retrieval.

b) If both systems share one common disconnected bus pair, the bus impedance is formed, using the algorithm in Eq. 9, and two systems are integrated to a partial system p_1, the process is shifted to the third subsystem retrieval.

c) If both system share two or more common disconnected but pairs, a partial system p_1 is formed for the one common bus pair, according to the preceding step b. And then for the remaining other bus pairs the bus impedance is forrned using the alogrithm in Eq. 10, successively one bus pair one time. After completing the assembling process, the process is shifted to the third subsystem retrieval.

5. At the third assembling stage, the third subsystem s_3 is retrieved, the same process as

c is repeated for s_1, s_2 and s_3 or p_1 (integration of s_1 and s_2) and s_3

6. And so forth.

The completion of the above assembling stages results in the formation of the total (original) system's bus impedance for the needed bus rows and columns only.

EXPANSION OF SEQUENCE BUS IMPEDANCE MATRICES BY FAULT BUS ADDITION

It is neccessary to define fault locations as new buses where faults occur at some locations along the line between system buses. But analysises for every varied fault location require the repeated computations for the corresponding sequence bus impedance matrices including a new fault bus or one computation for extravagantly large sequence bus impedance matrices expanded by a simultaneous addition of all fault buses. So this paper suggest a new approach for modifying the system bus impedances to those including a fault bus. This approach is based on the algorithms which follow:

〔**Algorithm 1.**〕 If a fault location is defined as bus f, the faulted line element starting at bus p and ending at bus q is magnetically coupled to a line element starting at bus r and ending at s (like double-circuit lines), the positive and negative sequence bus impedances for a balanced system are modified by an addition of bus f to.

$$\left.\begin{aligned} Z'^{\alpha}_{f,j} &= Z'^{\alpha}_{j,f} = \left\{ y^{\alpha}_{pf,pf}\cdot Z^{\alpha}_{p,j} + y^{\alpha}_{fq,fq}\cdot Z^{\alpha}_{q,j} \right\} \\ &\quad / \left\{ y^{\alpha}_{pf,pf} + y^{\alpha}_{fq,fq} \right\} \\ Z'^{\alpha}_{f,f} &= y^{\alpha}_{pf,pf}\cdot Z^{\alpha}_{p,f} + y^{\alpha}_{fq,fq}\cdot Z^{\alpha}_{q,f} + 1 \Big\} / \\ &\quad \left\{ y^{\alpha}_{pf,pf} + y^{\alpha}_{fq,fq} \right\} \\ Z'^{\alpha}_{i,j} &= Z^{\alpha}_{i,j} \end{aligned}\right\} \qquad (11)$$

which Z', Z=modified and unmodified bus impedance

α=1(positive sequence), 2 (negative sequence)

i, j=system bus, but $i \neq f$, $j \neq f$

$y^{\alpha}_{pf,pf} = 1/z^{\alpha}_{pf,pf}$, $y^{\alpha}_{fq,fq} = 1/z^{\alpha}_{fq,fq}$

$z^{\alpha}_{pf,pf}$, $z^{\alpha}_{fq,fq}$=positive or zero sequence primitive impedance of the pf and fq portion of faulted line element pq

〔**Algorithm 2**〕 In the same system mentioned in algorithm 1, the zero sequence bus impedances are modified to

$$\begin{aligned} Z'^{o}_{f,j} = Z'^{o}_{j,f} &= \{(y^{o}_{pf,pf} - y^{o}_{pf,fq})Z^{o}_{p,j} \\ &\quad + (y^{o}_{fq,fq} - y^{o}_{pf,fq})Z^{o}_{q,j} + (y^{o}_{rs,pf} - y^{o}_{rs,fq}) \\ &\quad \cdot (Z^{o}_{r,j} - Z^{o}_{s,j})\} / \{y^{o}_{pf,pf} + y^{o}_{fq,fq} - 2\cdot y^{o}_{pf,fq}\} \\ Z'^{o}_{ff} &= \{(y^{o}_{pf,pf} - y^{o}_{pf,fq})\ Z^{o}_{p,f} + (y^{o}_{fq,fq} - y^{o}_{pf,fq}) \\ &\quad Z^{o}_{q,f} + (y^{o}_{rs,pf} - y^{o}_{rs,fq})\cdot(Z^{o}_{r,f} - Z^{o}_{s,f}) + 1\} / \\ &\quad \{y^{o}_{pf,pf} + y^{o}_{fq,fq} - 2\cdot y^{o}_{pf,fq}\} \\ Z'^{o}_{i,j} &= Z^{o}_{i,j} \end{aligned} \qquad (12)$$

where
$$y^{o} \triangleq \begin{pmatrix} y^{o}_{rs,rs} & y^{o}_{rs,pf} & y^{o}_{rs,fq} \\ y^{o}_{pf,rs} & y^{o}_{pf,pf} & y^{o}_{pf,fq} \\ y^{o}_{fq,rs} & y^{o}_{fq,pf} & y^{o}_{fq,fq} \end{pmatrix} = \begin{pmatrix} z^{o}_{rs,rs} & z^{o}_{rs,pf} & O \\ z^{o}_{pf,rs} & Z^{o}_{pf,pf} & O \\ O & O & z^{o}_{fq,fq} \end{pmatrix}^{-1}$$

$z^{o}_{pf,pf}$=zero sequence primitive impedance of the pf protion of line element pq

$z^{o}_{rs,pf}$=zero sequence mutual impedance between lines rs and pf.

The sequence bus impedance modifications are required for every fault location, but no much time is consumed for the computation since the system bus impedances in which the fault bus is undefined have already been computed.

COMPUTATIONS OF FAULT VOLTAGES AND CURRENTS

Where a fault occures at location f, each seqence component of fault current at f, $i^{\alpha}_{f(F)}$ is computed as [2]

$$\left.\begin{aligned} i^{\alpha}_{f(F)} &= (Z_F{}^{\alpha} + Z^{\alpha}_{f,f})^{-1} E^{\alpha}_{f(o)} \\ \text{or}\quad i^{\alpha}_{f(F)} &= Y_F{}^{\alpha}(U + Z^{\alpha}_{f,f}\cdot Y_F{}^{\alpha})^{-1}\cdot E^{\alpha}_{f(o)} \end{aligned}\right\} \qquad (13)$$

where $Z_F{}^{\alpha}$, $Y_F{}^{\alpha}$=seqence fault impeadance, admittance matrix.

$E^{\alpha}_{f(o)}$=sequence voltage prior to the fault at f. And each sequence voltage after the fault at bus i $E^{\alpha}_{i(F)}$ is computed as [2]

$$E^{\alpha}_{i(F)} = E^{\alpha}_{i(o)} - Z^{\alpha}_{i,f}(Z_F{}^{\alpha} + Z^{\alpha}_{f,f})^{-1}\cdot E^{\alpha}_{f(o)} \qquad (14)$$

where $E^{\alpha}_{i(o)}$=sequene voltage prior to the fault at i bus. consequently, each sequence current in the network element ij after the fault is computed on the equivalent network basis as

$$i^{\alpha}_{ij(F)} = y^{\alpha}_{ij}\ (E^{\alpha}_{i(F)} - E^{\alpha}_{i(F)}) \qquad (15)$$

where $i,j \mp pf, fq$, or rs in Eqs. 11 and 12 where each sequence current in the faulted line elment portions pf and fq, and the element coupled with them is computed on the actual network basis as

$$i^{\alpha}_{uv(F)}=y^{\alpha}_{uv,rs}\,(E^{\alpha}_{r(F)}-E^{\alpha}_{s(F)})+y_{uv,pf}$$

$$(E^{\alpha}_{p(F)}-E^{\alpha}_{f(F)}+y^{\alpha}_{uv,fq}\,(E^{\alpha}_{f(F)}-E^{\alpha}_{q(F)}) \qquad (16)$$

where $uv=rs,pf$ *or* fq.

$\alpha=1,2$

$$i^{o}_{uv(F)}=y^{o}_{uv,uv}\{E^{o}_{u(F)}-E^{o}_{v(F)}\} \qquad (17)$$

CONCLUSIONS

1. The suggested approach in this paper for analysis of faults is applicable to any large power system and any small-scale computer of core-memory limited type.

2. The suggested approach does not increase a substantial amount of computational time, and in some case decreases computational time rather than the conventional method for fault analysis.

3. The fortran program by this approach was already applied to the fault analysis of Korean Power System(about 80 buses and 140 network elements) including double-circuit lines to obtain fundamental data for electromagnetic induction to the adjacent communication lines, and its usefulness and efficiency has been favorably justified by the results.

4. The computer used for the Korean Power System is the CDC 3300 machine having 96-K word core memory and could not carry out continously the fault analysis by means of the conventional method. But the application of the suggested approach to this computer ensured the continous analysis with varied fault locations without spending core memory spaces too much.

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