FUZZY-BASED MULTI-AGENT APPROACH FOR RELIABILITY ASSESSMENT AND IMPROVEMENT OF POWER SYSTEM PROTECTION

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ABSTRACT

Assessment of reliability is one of the important topics in a power system which needs more decentralized mechanism to enable an electrical load to continue receiving the power in the event of its disconnection from the main power grid. Despite the huge remarkable breakthrough in software technologies, most judgements have to be based on human experts in most of the planning and operation in power system. Most of the techniques are used to address the power system reliability which consumes long computation time. Hence, an inaccurate result for system operators is inevitable as most of the variables affecting the reliability changes with time. As a result of this setback, Multi Agent System (MAS) and Fuzzy models could be used as a reliable assessment of such challenges. MAS is a collection of agents that have been applied to several power system problems such as, those in operation, markets, diagnosis and protection. In this study, in order to assess the system reliability, distribution protection system design and coordination, two models of MAS techniques to determine the suitability of the Distributed Generator (DG) location based on power system reliability and new index reliability of the relay operating time are proposed. The first MAS model is designed using three agents. The first agent is a grounding indices, which is responsible for installing DG randomly by grounding indices. The second agent is a reliability evaluation agent that uses a recursive algorithm to predict the suitability generator based on the frequency and duration reliability indices in each state while the third agent is the storage and transfer of data between the other two agents. Meanwhile, the second MAS model has been designed using two agents as follows: the first agent is a fault current agent that is to determine the fault current at all points before and after grounding; the second agent is the time operating of the agent which is used to determine the relay operating time before and after modifying fault current. The simulation results for the first and second models are done using the data obtained from Malaysia distribution network (DISCO-Net) and 69 bus test system that were implemented using Java Agent Development Framework package software. The simulation results show the effectiveness of proposed MAS approaches for selecting the best DG location in a function of improved power system grounding and reliability. Meanwhile, the simulation results for second model shown that the failure rate decreased to approximately 40% for over current and earth fault relays. The fast reliability indices are also obtained in assessing the performance of the protection system from the selection of DISCO-Net. Finally, to improve the evaluation of the reliability, the approaches of using MAS for connection of probability with the reliability fuzzy model is proposed. The probability agent is to determine the capacity in service while a fuzzy model agent is to estimate the operation or failure probability. In addition, another two agents have been developed based on Monte Carlo simulation. The first agent employed fuzzy parameters such as, current with its means and variances and the second agent is the probability of outage capacity for each state. All these agents have been applied in terms of the loss of load probability (LOLP) and loss of load expectation (LOLE), which have been implemented based on a IEEE-57 bus test system and DISCO-Net. The outcomes had shown that the fuzzy parameters of Monte Carlo simulation provided a better limitation for variance techniques in uncertainty load levels.

ABSTRAK

Penilaian kebolehpercayaan adalah salah satu aspek yang penting dalam sistem kuasa elektrik. Hal ini demikian kerana sistem ini memerlukan sebuah mekanisme yang lebih berpusat, iaitu sebuah mekanisme yang membolehkan tenaga elektrik secara terus menerus diterima walaupun berlakunya pemberhentian grid dari sumber utama. Walaupun berlakunya perkembangan yang pesat dalam bidang teknologi perisian, namun begitu sebahagian besar daripada aspek perancangan dan operasi di dalam sebuah sistem kuasa elektrik masih memerlukan pertimbangan dan khidmat kepakaran manusia. Masa yang panjang juga digunakan untuk menangani kebanyakan teknik yang digunakan sebagai penilaian kebolehpercayaan dalam sistem kuasa elektrik. Pengendali sistem ini tidak dapat mengelak daripada menerima keputusan yang tidak tepat. Hal ini kerana kebanyakan pembolehubah yang digunakan untuk menilai kebolehpercayaan ini adalah bergantung kepada aspek masa dan setiap pembolehubah akan berubah mengikut tempoh masa. Berdasarkan kemunduran dan cabaran ini di dapati Sistem Multi Agen (MAS) dan model "Fuzzy" digunakan sebagai teknik untuk penilaian kebolehpercayaan ini. MAS merupakan agen yang digunakan dalam sistem kuasa untuk mengatasi beberapa masalah berkaitan dengan aspek pengoperasian, pemasaran, penilaian dan perlindungan. Dalam kajian ini dua model teknik MAS akan digunakan untuk menilai kebolehpercayaan sesebuah sistem seperti sistem pengaliran perlindungan reka bentuk dan penyelarasan yang bertujuan untuk menentukan kesesuaian lokasi pengagihan Generator (DG). Hal ini adalah untuk mengantikan penilaian kebolehpercayaan sistem sumber kuasa dengan indeks penilaian baru yang dicadangkan. Model MAS yang pertama direka menggunakan tiga agen. Agen yang pertama ialah indeks asas (bertanggunjawab untuk memasang DG secara rawak oleh pembumian indeks), agen kedua, iaitu agen penilaian kebolehpercayaan (yang menggunakan algoritma rekursi untuk meramalkan penjana kesesuaian berdasarkan indeks kekerapan dan kebolehpercayaan tempoh di setiap negeri) dan agen yang ketiga, iaitu agen penyimpanan dan pemindahan data antara dua agen. Seterusnya model MAS kedua telah direka menggunakan dua agen. Agen yang pertama ialah kesalahan agen semasa (iaitu untuk menentukan arus kerosakan pada setiap mata sebelum dan selepas pembumian) dan agen kedua adalah masa beroperasi agen itu (iaitu digunakan untuk menentukan masa operasi geganti sebelum dan selepas mengubahsuai kesalahan semasa). Keputusan simulasi untuk model pertama dan kedua yang diperolehi berdasarkan data yang diperolehi daripada rangkaian pengedaran Malaysia (DISCO-Net) dan sistem ujian terhadap 69 buah bas yang dilaksanakan menggunakan pakej perisisian Rangka Kerja Pembangunan Agen. Keputusan simulasi menunjukkan bahawa keberkesanan yang dicadangkan oleh model MAS merupakan sebuah pendekatan yang terbaik untuk memilih fungsi lokasi DG dan penilaian sistem kebolehpercayaan, Sementara itu, keputusan simulasi untuk model kedua menunjukkan bahawa kadar kegagalan menurun kepada kira-kira 40% lebih geganti kesalahan semasa dan bumi. Indeks kebolehpercayaan cepat juga diperolehi untuk menilai prestasi sistem perlindungan daripada pemilihan DISCO-Net. Akhir sekali, untuk meningkatkan penilaian kebolehpercayaan, pendekatan menggunakan model MAS dan model kebolehpercayaan kabur telah dicadangkan. Agen kebarangkalian adalah untuk menentukan keupayaan dalam perkhidmatan manakala agen model kabur adalah untuk menganggarkan jumlah operasi atau kegagalan kebarangkalian. Namun begitu, terdapat juga dua agen lain yang turut dibangunkan berdasarkan simulasi Monte Carlo. Agen pertama bertindak sebagai model kabul untuk parameter, iaitu melakukan tinjauan semasa dan melihat bentuk perbezaan yang berlaku. Seterusnya agen kedua, iaitu kebarangkalian kapasiti gangguan bagi setiap negeri. Semua agen-agen ini hendaklah digunakan dari segi kehilangan kebarangkalian beban (LOLP) dan kehilangan harapan beban (LOLE), yang telah dilaksanakan berdasarkan IEEE-57 sistem ujian bas dan DISCO-Net. Hasil keputusan telah menunjukkan bahawa parameter kabur simulasi Monte Carlo menyediakan had yang lebih baik untuk menentukan teknik varians dalam tahap beban yang tidak menentu.

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LIST OF ABBREVIATIONS

A	Availability
ACL	Agent Communication Language
CDC	Communication Data Center Agent
COPT	Capacity Outage Probability Table
CT	Current transformer
DER	Distributed Energy Resources
DG	Distribution generators
DT	Definite Time
ECS	Energy Capacitor System
EENS	Expected Energy Not Supplied
EF	Earth Fault relay
EI	Extremely Inverse
EIR	Energy Index of Load Reliability
FAD	Frequency and Duration
FIPA	Foundation for Intelligent Physical Agents
FOR	Forced Outage Rate
GAs	Generator Agents
HL	Hierarchical Levels
HL-I	Hierarchical Level-I
HL-II	Hierarchical Level II
HL-III	Hierarchical Level III
IGA	Indexes Grounding Agent
ISOs	Independent System Operators
JADE	Java Agent Development Framework
KQML	Knowledge Query and Manipulation Language
LA	Load Agent
LOEE	Loss of Energy Expectation
LOEP	Loss of Energy Probability
LOLD	Loss of Load Duration
LOLE	Loss of Load Expectation

LOLF	Loss of Load Frequency
LOLP	Loss of Load Probability
LPT	Load Probability Table
MA	Master Agent
MAS	Multi agent system
MCS	Monte Carlo Simulation
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NERC	North American Electric Reliability Council
OC	Overcurrent relay
PCC	Point of Common Coupling
PSM	Plug Setting Multiplier
RA	Reliability Agent
RAG	Recursive Algorithm Agent
RE	Renewable Energy
SAs	Switch Agents
SBAs	Substation Breaker Agents
SI	Standard Inverse
TBAs	Tie Breaker Agents
TMS	Time Multiplier Setting
VI	Very Inverse

LIST OF SYMBOLS

C_i^M	Number of MWs of load for system state *i*
µ	repair rate
$\mu(P_j)$	Membership Grades of capacity level j
C	Capacity System
C_s	Capacity in service
D	Mean duration
Dn	Number of the days
D*i*	Duration of system state i
F	Fault Frequency
$f(I_{\sigma i})$	Fuzzy of Load Exceeding capacity in service
F_j	Frequency of departing system state *j*
f_j	portion of F_j
Gr. DG	Number of generator grounded
G_{rm}	Reserve Margin
i	identical states
I_f	fault current
I_p	pick up current
LMAs	Management Agents
L_P	Total system load demand
n	cumulative state after achieving terms of grounding indexes
N	Number of capacity levels
P	individual probability
$P(C-I_i)$	Probability of Capacity outage
$P(P_j < r_i)$	Probability Fuzzy logic
P_i	Probability of system state i
P_j	Available unit capacity levels j
Q	unavailability
R_0	zero sequence resistance
S	Set of all possible system states associated with loss of load
T	Time cycle

Ti	Time unit of the index
t_i	Time interval of capacity in outage
TOP	Operating Time of Relay
V_D	overvoltage during single line to ground fault (L-G)
X_0	zero sequence reactance
X_1	positive sequence reactance
X_k	Standard normal distribution
α	Cut set factor
λ	failure rate
σi	Standard Deviation of group

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

A crucial role of an electric power system is to generate electricity to meet the customer demands, with an acceptable level of reliability in an economical manner. The main functional areas in an electric power system are generation, transmission and distribution. The function of the generation system is to make sure enough capacity is available to meet the load/demand at any time. Transmission and distribution systems need to be reliable to ensure the electricity can be delivered to the consumers.

Therefore, reliability assessment is one of the most significant assignments of power system operation. In other sides, it is important to make proper plan and maintain a reliable electric power system because the expenditure of outages, and the cost of power interruptions contribute to economic influence on the companies and its customers. With a view to resolve the odds between the economic and reliability limitations, a wide range of techniques and standards have been developed such as the failure and repair rates of equipment and operating practices, Monte Carlo (MC) simulation technique, and maintenance schedules.

The reliability of an electric power system is defined as the probability that the power system will perform the function of delivering electric energy to customers on a continuous basis and with acceptable service quality (Bhavaraju et al., 2007). Probabilistic method is often used to determine the system reliability and the system reliability can be summed up into a single value, the reliability indices such as loss of load probability and loss of load expectation. The reliability evaluation can be divided into two parts: modelling of the reliability characteristics of the components and the calculation of the reliability of the system.

Distributed generation (DG) is a small generation unit with lower operational capacity in comparison with large power plants, which uses clean and environmentally compatible energy resources to produce electricity. Due to small generation capacity, it is not economical to transfer their energy productions through the power transmission lines. Thus, DGs are generally connected to distribution systems (Barker and DeMello, 2000). Consequently, determining the accurate location of probable faults is more important in distributed systems that includes DG (Javadian and Haghifam, 2008).

Recently, exploitation of DG is predicted to play an important role in the electric power system in terms of reducing cost of energy in the high load level, security improvement, interconnection and reliability improvement. When the DGs are connected into the distribution power grid, the grounding methods should be taken into account. Generally, there have been the topics on the practice of grounding power system, which are firstly, from the ungrounded system, impedance as resistance or reactance grounded until the recent of solidly grounded and effectively grounded. For using a DG without a transformer, special attention should be paid to the zero sequence impedance design so that effective ground can be provided. Unlike the DG with a transformer, this has been provided with effective grounded. The DG without a transformer must shape the zero sequence impedance characteristic using an active control approach (Kroposki, 2003).

The protection relays (over current relay and earth fault relay) of the power system are based on three principles in its operation, i.e., the type of fault, the fault location and the number of interconnections. Therefore, the DGs can be installed as additional contribution to the fault level. The setting of protection relays that were formerly prepared for the system without DGs may not significantly manage the faults (Wan et al., 2008).

There is more evidence that protection systems play a role in the origin and propagation of major power system disturbances. The relay can detect abnormal power system conditions, and initiate action as quickly as possible in order to isolate the faulted component and return the rest of the system to the normal condition. So, the protection relays can exchange the information to protect the power system in a more intelligent and reliable way. The protection equipment reliability indices are determined by using real data analysis that provides more accurate or realistic information as it uses the past failure data of the relays.

The protection relays and the installed DG produce a reliable system, providing a set of probabilities of a reliable solution, for a bus bars power plants generation or distribution. Nowadays, the reliability assessment methods are advanced in its analysis, which is one of them is probabilistic technique. The probabilistic technique has been extensively employed in generation, planning and distribution systems design and some of commercial software packages. Considerable progress also has been made in power system reliability modelling and computation based on probability theory (Billinton and Kuruganty, 1981; Cheng et al., 2000).

Many methods also have been developed and widely used in evaluating the electric power system reliability indices. One of them is the recursive algorithm that is more practical approach for large system analysis. The analysis can be used for two-state or multi-state unit and provides a fast technique for building capacity models (installing new units), and the algorithm can also be used to remove a unit.

Meanwhile, fuzzy set theory is originally introduced by Zadeh in 1965, as a mathematical way to represent vagueness in everyday life, it also provides a useful tool for reliability evaluation for power system, in which the probabilities or/and performance rate of the system elements that cannot be certain. In applying the theory of fuzzy set and possibility to the analysis of real-world problems, it is natural to adopt the view of imprecision in primary data which is in general induce imprecision in the results of the analysis. The theory of fuzzy sets provides a framework for dealing with such variables in a systematic way and thereby opens the door to apply fuzzy knowledge-based techniques to reliability analysis (Cai, 1996).

Probability methods alone are not sufficient to deal with the problems of reliability, and as a solution, fuzzy set could be used to address such problems (Bowles et al., 1995). The fuzzy set algorithm is used to determine uncertainty processing to improve reliability by one of the important factors in taking inference procedures and decision-making and fault detection in a power system is the membership functions

(Momoh et al., 2000). According to Sérgio Ramos et al., (2009), the probability simulation by mathematical model of randomness and fuzzy set have been used in his research. The fuzzy set is the focus of intense attention in many areas to solve power system reliability. Choi et al., (2002), has presented a new fuzzy operation of area under the load duration curve model for evaluating reliability indices of composite power systems based on probability and fuzzy set methods. Meanwhile, Saraiva et al., (1996), has used fuzzy load description in generation and transmission power system reliability using Monte Carlo method.

The standard deviation of load level uncertainty in power system reliability assessment has a different value for each load level that leading to complexity of iterations required in the convergence of MC algorithm. The MC has been defined as one of the stochastic techniques (Brown, 2002; Haroonabadi and Haghifam, 2008), that is based on the use of random numbers and possibilities calculations for investigating the problems.

Multi-Agent System (MAS) is a computerized system in which several agents cooperate to achieve a particular task. MAS are essentially developed as a control and reconfiguring the system. The concept of single agent system has to be understood before one starts looking into MAS. The agent has been defined in many different ways, and a few definitions are provided as below. Agents are able to sense the local environment and interacting with other agents in its local environment. Java Agent Development Framework (JADE) is typically the most famous representative middleware with accessories of agent program and a development package. JADE emerged by the Research and Development department of Telecom Italia (Sridhar, 2009). JADE gives the development of unparalleled software agents that can perform a control task, and helps decentralize control architectures (Colson et al., 2011).

Nowadays, MAS have been applied to enhance the problem in power systems (McArthur et al., 2007), such as voltage stability, electricity markets pricing and protection coordination. Very limited study has been done in installing DG location. Therefore, the approach of multi-agents for solving power system reliability problems are proposed. In implementation, a thorough investigation on the various modelling, protection and reliability assessment are necessary for developing an effective detection technique (Nagata and Sasaki, 2002).

In order to achieve the reliability assessment, it must develop each agent an effective communication within the platform and globally build a working relationship as they negotiate towards the laid criterion (Anant and Kenedy, 2009). Also, the agents are the focus of intense attention in many areas such as computer science and artificial intelligence. In fact, agents have been used increasingly in variety of applications (Nagata and Sasaki, 2002). A multi-agent system is a system composed of multiple interacting intelligent agents.

In this present work, a new philosophy has been developed for the improvement of the reliability power system, making use of three different parameters, which consist of the protection relays, an installation of DG and calculations of reliability indices with respect to their various probabilities, which have been determined by effective grounding. Fuzzy calculation (reliability indices) and the developed MAS have been used to select the best probability from these parameters by investigating the problems and detecting any type of disturbances in the power system. This then solve by interactions between these parameters and proffering a solution with the best probability.

1.2 PROBLEM STATEMENT

The technology developments in the form of technological innovations with relation to power system protection and distribution networks are important in order to enable an electrical load to continue in receiving the power in the event of disconnection from the main power grid. From the existing techniques that have been used for solving power system problems indicated that, there is a need to develop an accurate technique in practical or for real time applications, which is more complicated. In other words, it could be used to strengthen the decision making process by the operators and choose the best reconfigurable when there are some generators in an outage. Nevertheless, the investigation of the various modelling of reliability indices in a power system generation are necessary in order to develop effective detection technique for vorious parameters affecting in reliability. The problem statement of this work can be summarized as follows:

1. For a system to be effectively grounded, all system points or in specified portion, the ratio of zero-sequence reactance to positive-sequence reactance is not greater than “three” while the ratio of zero-sequence resistance to positive-sequence reactance is not greater than “one” for any operational of condition: this system may be considered as effectively grounded (Nelson and John, 2003). The third condition of which unfaulted phases may be subjected to over-voltages in which the absolute value of overvoltage during single line to ground fault (L-G) whereby one voltage phase varies from 0.866 pu to 1.732 pu. It should be noted that, transformer without impedance characteristic should be effectively grounded, but these are lacking in most designs. Therefore, the study on the effect of different transformer arrangements and the grounding types on DG location (i.e., grounded or ungrounded) are vital (Martinez and Martin-arnedo, 2009).
2. The protection relay manufacturers only describe the reliability of their apparatus in accordance to Mean Time Between Failures (MTBF), whereby the actual reliability figures of the relays may vary depending on the relay installation and operation over a period of time. The characteristics of each relay have been published by the manufacturers as a set of curves conformable to different values of time dial settings (Mohd Iqbal et al., 2011).
3. Uncertainties in the power system are divided into two types: randomness and fuzziness (Li et al., 2008). The reliability indicators can be probabilistic according to power demand, reserve margin, obtainable historical data and load forecasting while fuzzy methods are based on probabilities of these variables. This means that the problem of the variables changing with the times affecting the reliability has caused inaccurate results of system operation, which are still lacking in most approaches. Another problem is in the calculation of the standard deviation of load level uncertainty in power system reliability assessment, which has a different value for each load level. This has led to complexity iterations required in the convergence of MC methods.

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CHAPTER 3

DG LOCATION AND PROTECTION RELAYS USING MAS TO IMPROVE RELIABILITY ASSESSMENT

3.1 INTRODUCTION

This Chapter describes the methods and variables used in order to carry out the research and simulated procedure. The study is conducted in two stages; the first stage is the grounding analysis for a new technique for selecting the best DG location by using MAS and secondly a new index reliability for determining relay operating time based on MAS. The implementation of the proposed methods for real time data is also elaborated.

3.2 DISTRIBUTED GENERATOR (DG)

DG provides many advantages in term of improvements in losses and reliability, or both (Yousefian and Monsef, 2011). In addition, there are many DGs locations which can lead to minimize fault current in the event of faults and provide the necessary effective grounding to solve bus voltage problems when unfault phases over voltage in bus are encountered.

3.2.1 System Effectively Grounded with DG

When DGs are connected into the distribution power grid, the grounding methods should be taken into account. There are many types of grounding, e.g., solid grounding, resistance or reactance grounding and isolated grounding. In the last decade, the phrase of “solidly grounded” has replaced to the newer “effectively grounded” for a reason of no auxiliary grounding devices (resistors, reactors, neutralizers, etc.) that are ordinarily required. In effectively grounded system, all faults including grounds must be cleared by opening the line. The ground fault currents close to the grounding point are high, in some cases exceeding the three phase short circuit currents. In a few instances, higher interrupting capacity breakers may be required over that necessary for the three-phase short-circuit interruption. The higher currents also produce more conductors burning and result in lower positive-sequence voltages with a tendency toward a lower stability limit for line-to-ground faults. In addition, the effectively grounded systems are less expensive than any other type of grounding.

For using a DG without a transformer, special attention should be paid to the zero sequence impedance design so that effective ground can be provided. Unlike the DG with a transformer providing the effective ground passively, the DG without a transformer must shape the zero sequence impedance characteristic using an active control approach (Kroposki, 2003). For a system effectively grounded, all system points or in specified portion, the ratio of zero-sequence reactance to positive-sequence reactance is not greater than "three" while the ratio of zero-sequence resistance to positive-sequence reactance is not greater than "one" for any operational condition, the system may be considered as effectively grounded (Nelson and John, 2003) when the following conditions in Equation (3.1) are met:

$$1 < \frac{X_0}{X_1} < 3 \quad \& \quad 0 < \frac{R_0}{X_1} < 1 \tag{3.1}$$

where, X_1 is positive sequence reactance, X_0 is zero sequence reactance and R_0 = zero sequence resistance.

The third condition is unfaulted phases may be subjected to over-voltages in which the absolute value of overvoltage in per unit is given as in the following Equation (3.2) (Balakrishnan, 2008):

$$V_D = \sqrt{\left(\frac{\sqrt{3}}{2}\right)^2 + \left(\frac{1}{2} + \frac{\left(\frac{X_0}{X_1}\right) - 1}{\left(\frac{X_0}{X_1}\right) + 2}\right)} \tag{3.2}$$

where; V_D is overvoltage during single line to ground fault (L-G) in which voltage one phase varies from 0.866 pu to 1.732 pu.

For a power system with *m*-buses, the bus relation between voltage and current may be represented as a bus impedance matrix given in Equation (3.3). Unlike the bus admittance matrix, the bus impedance matrix cannot be formed by simple examination of the network circuit. It can be formed by direct inversion of the admittance matrix, open circuit testing, and step-by-step formation or graph theory (Saadat, 2004).

$$\begin{vmatrix} V_1 \\ \vdots \\ V_m \end{vmatrix} = \begin{vmatrix} Z_{11} & \cdots & Z_{1m} \\ \vdots & \ddots & \vdots \\ Z_{m1} & \cdots & Z_{mm} \end{vmatrix} \begin{vmatrix} I_1 \\ \vdots \\ I_m \end{vmatrix} \tag{3.3}$$

where, $Z_{11} = R_{11} + jX_{11}$. By considering the faulty case as given in L-G fault for bus *m*, the sequential components of the line-to-ground voltages at any bus *m* during a fault at bus *n* are given by Equation (3.4) (Appendix C).

$$\begin{bmatrix} V_{m-0} \\ V_{m-1} \\ V_{m-2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_F \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{mn-0} & 0 & 0 \\ 0 & Z_{mn-1} & 0 \\ 0 & 0 & Z_{mn-2} \end{bmatrix} \begin{bmatrix} I_{n-0} \\ I_{n-1} \\ I_{n-2} \end{bmatrix} \tag{3.4}$$

Therefore, the short-circuit calculations with a bus impedance matrix of symmetrical components of a fault current (single line to ground fault) can be computed as Equation (3.5) (Appendix C).

$$I_m^0 = I_m^1 = I_m^2 = \frac{V_F}{Z_{mm}^0 + Z_{mm}^1 + Z_{mm}^2 + 3Z_F} \tag{3.5}$$

where, Z^1_{mm} , Z^2_{mm} *and* Z^0_{mm} are the diagonal elements in the *m-axis* of the corresponding impedance matrix , Z_F is a fault impedance and V_F is the pre-fault voltage at bus *m*.