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Application of RGA to Optimal choice and Allocation of UPFC for Voltage Security Enhancement in Deregulated Power System

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Abstract: Voltage stability becomes a crucial issue in power systems especially under heavily loaded conditions. The main purpose of this paper is to identify the optimal location of Unified Power Flow Controller (UPFC) to enhance power system voltage stability by using real genetic algorithm (RGA). The proposed method demonstrates the improvement of voltage stability margin by implementing to a modified IEEE case study.

Key-Words: Voltage stability, Voltage collapse, UPFC, Real Genetic Algorithm (RGA), FACTS Devices

1 Introduction

Voltage collapse phenomena in power systems have become one of the important concerns in the power industry over the last two decades, as this has been the major reason for several major blackouts that have occurred throughout the world including the recent Northeast Power outage in North America in August 2003. Point of collapse method and continuation method are used for voltage collapse studies [l]. Of these two techniques continuation power flow method is used for voltage stability analysis. These techniques involve the identification of the system equilibrium points or voltage collapse points where the related power flow Jacobian becomes singular [2, 3].

The voltage collapse occurs when a system is loaded beyond its maximum loadability point. Voltage collapse studies are carried out with the aim to maximize the loading capability of a particular transmission line. Traditionally shunt and series compensation is used to maximize the transfer capability of a transmission line [4]. Recently the new concept of Flexible AC Transmission System (FACTS) was developed by Electric Power Research Institute (EPRI), which involves a family of fast acting, high power electronic devices. FACTS controllers provide fast and reliable control over the three main transmission parameters, i.e., voltage magnitude, phase angle and line impedance. For this reason, control of FACTS devices has received a lot of attention in power system stability enhancement [5]. Using FACTS controllers, like Static Var Compensator (SVC) and Static Phase Shifter (SPS), to improve transient stability has been explored in the past years and is shown to be effective [6].

In this research voltage stability enhancement is modeled as an optimization problem and Unified Power Flow Controller (UPFC) is applied to improve voltage stability margin.

This paper is organized as follows: in section 2 the optimization problem is defined and formulated. RGA algorithm is described in section3. Section 4 presents Simulation tools and Section 5 presents the simulation results through a case study which followed by concluding remarks as section 6.

2 Problem Formulation

Nonlinear dynamical systems such as power systems can be generally described as follows:

$$\dot{x} = f(x, \lambda, p) \tag{1}$$

Where:

$x \in R^n$: Corresponds to state variables

$\lambda \in R^1$: Represents a particular set of non-controllable parameters that drive the system to bifurcation in a quasi-static manner. λ causes the system steadily moves from one equilibrium point to another.

$p \in R^K$: Represents a series of controllable parameters associated with control settings.

In this research λ is the distance between operating and voltage collapse points. The maximum λ will be determined through

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optimization process considering employing UPFC. Optimization problem can be formulated as:

$$\text{Max} \quad F(u) = (\lambda - \lambda_0)$$

$$\text{S.t} \quad C(u) = \begin{bmatrix} F(x,\lambda,p_0) \\ D_x^T F(x,\lambda,p_0) w \end{bmatrix} = 0 \qquad (2)$$

$$u = (x,\lambda,w,p)$$

Where:

$D_xF|_*$: Corresponding system Jacobian

w: is normalized right "zero" eigenvectors in R^n of $D_xF|_*$.

Thus, the idea is to maximize the distance between a given operating point defined by λ_0 and the collapse point[7].

2.1 UPFC Basic Concept

UPFC is constructed from two power electronic converters, the series converter and the shunt converter, which are connected together by a common DC link as shown in Fig. 1 [8].

The series converter is connected in series with the transmission line through a series transformer. It injects a voltage $\overline{V}_B$, in series with the line, whose phase angle can vary between 0 to 2π with respect to the terminal voltage and whose magnitude *can* vary from 0 to a maximum value determined by the device rating. The shunt converter is connected parallel with the line through a shunt transformer. Its main function is to provide real power required by the series converter plus losses by regulating the DC bus voltage at a desired value. It can also operate as an independent reactive power compensator.

The common DC capacitor C_{dc} provides a direct voltage support for the converter operation and also functions as an energy store. As can be seen, there are three controllable parameters: the magnitude and phase angle of the series injected voltage and the shunt reactive power compensation. They can be controlled in a variety of ways to meet different objectives. This has made UPFC very flexible to control for a specific application.

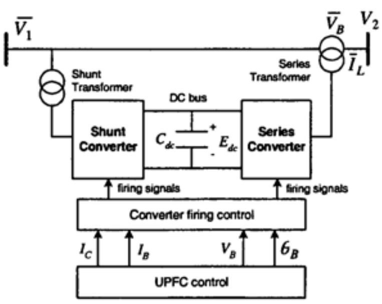

Fig.1. Schematic structure of UPFC

2.1.1 UPFC Steady State Injection Model

The steady state injection model of UPFC can easily incorporate the UPFC into the power flow equations [9].Fig.2 shows the UPFC circuit arrangement. The series converter is represented by an AC voltage source in series with a reactance X_s. UPFC injection model is derived as follows:

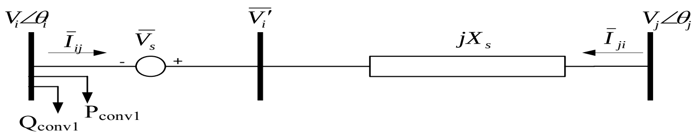

Fig.2. UPFC circuit arrangement

First it is necessary to consider only the series voltage source. The voltage $\overline{V}_i'$, and the current $\overline{I}_{ij}$ are defined as :

$$\overline{V}_i' = \overline{V}_i + \overline{V}_s \qquad (3)$$

$$\overline{I}_{ij} = \frac{\overline{V}_i - \overline{V}_j}{jX_s} \qquad (4)$$

The series voltage source $\overline{V}_s$ is controllable in magnitude and phase i.e.:

$$\overline{V}_s = r\overline{V}_i e^{j\gamma} \qquad (5)$$

Where $0 < r < r_{max}$ *and* $0 < \gamma < 2\pi$

In the next step, the series voltage source is transformed to a current source, $I_s = -jb_s\overline{V}_s$, in parallel with the line, where $b_s = \frac{1}{X_s}$ as shown in Fig.3.

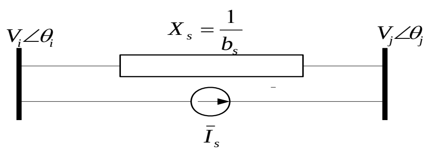

Fig.3. Transformed series voltage source

The current source $\overline{I}_s$ corresponds to the injection powers at buses i and j as follows:

$$\overline{S}_{is} = \overline{V}_i(jb_s\overline{V}_s)^* = -rb_sV_i^2\sin\gamma - jrb_sV_i^2\cos\gamma \qquad (6)$$

$$\overline{S}_{js} = \overline{V}_j(-jb_s\overline{V}_s)^*$$
$$= rb_sV_iV_j\sin(\theta_{ij}+\gamma) + jrb_sV_iV_j\cos(\theta_{ij}+\gamma) \qquad (7)$$

Where $\theta_{ij} = \theta_i - \theta_j$

The series voltage source injection model can be seen as two dependent loads as shown in Fig.4.

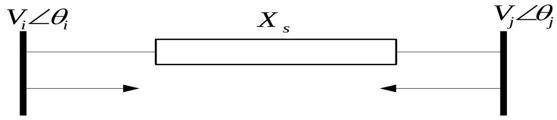

Fig.4 Injection model of series voltage secure

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$$P_{si} = rb_s V_i^2 \sin(\gamma) \quad (8)$$

$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ji} + \gamma) \quad (9)$$

$$Q_{si} = rb_s V_i^2 \cos(\gamma) \quad (10)$$

$$Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma) \quad (11)$$

2.1.1.1 UPFC Model

The apparent power supplied by the series voltage source converter is calculated from

$$\overline{S}_{conv2} = \overline{V}_s \overline{I}_{ij}^* = re^{j\gamma}\left(\frac{\overline{V}_i' - \overline{V}_j}{jX_s}\right)^* \quad (12)$$

The active power supplied by converter 1 is

$$\begin{aligned} P_{conv1} &= P_{conv2} = \mathrm{Re}(S_{conv2}) \\ &= rb_s V_i V_j \sin(\theta_{ij} + \gamma) - rb_s V^2{}_i \sin(\gamma) \end{aligned} \quad (13)$$

The reactive power delivered or absorbed by the converter 1 is independently controllable by UPFC and can be modeled as a separate controllable shunt reactive source Q_{conv1}.

The UPFC injection model is constructed from the series voltage source (Fig. 4) with the addition of a power equivalent to $P_{conv1} + jQ_{conv1}$ to node i as shown in Fig.5.The model can be incorporated to the power flow equations by including b_s into the bus admittance matrix and adding the UPFC injection powers at buses i and j [10].

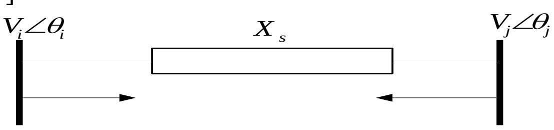

Fig.5. UPFC injection model

$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) \quad (14)$$

$$P_{sj} = -rb_s V_i V_j \sin(\theta_{ji} + \gamma) \quad (15)$$

$$Q_{si} = rb_s V_i^2 \cos(\gamma) + Q_{conv1} \quad (16)$$

$$Q_{sj} = -rb_s V_i V_j \cos(\theta_{ji} + \gamma) \quad (17)$$

2.2 UPFC Cost Function

The capital cost function of UPFC can be represented as Equations (18) respectively [11].

$$C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22 (US\$/KVAr) \quad (18)$$

Where: C_{UPFC} is in US$/KVAr and *S* is the operating range of the FACTS devices in *MVAr*.

3 Solution Algorithm

Heuristic methods may be used to solve complex optimization problems. They are able to give a good solution of a certain problem in a reasonable computation time, but they do not assure to reach the global optimum. GA is a global evolutionary search technique that can result a feasible as well as optimal solutions. GA starts with a random initial population in order to select the best individuals. Crossover and mutation and selection all together are the functions of associated with GA to handle the evolutionary search reaching the best solution. Ordinary (binary) GA can be modified using real codes as real-GA (RGA), in which decoding is not needed to be done, while it may increase the speed and the accuracy of search process. The major issues of RGA can be addressed in crossover as well as mutation and selection stages. In the following those stages are explained in details [12].

3.1 Crossover

Crossover is one of the main features of RGA that makes it different from binary GA. Three kinds of convex crossover technique are used in this paper based on the following formulas [13]:

$$\begin{aligned} O_1 &= \lambda P_1 + (1-\lambda) P_2 \\ O_2 &= \lambda P_2 + (1-\lambda) P_1 \qquad \lambda \in \{0,1\} \end{aligned} \quad (19)$$

$$\begin{aligned} O_1 &= \lambda_1 P_1 + (1-\lambda_1) P_2 \\ O_2 &= \lambda_2 P_2 + (1-\lambda_2) P_1 \qquad \lambda_1, \lambda_2 \in [0,1] \\ O_1 &= \lambda P_1 + (1-\lambda) P_2 \\ O_2 &= \lambda P_2 + (1-\lambda) P_1 \qquad \lambda \in [-0.25, 1.25] \end{aligned} \quad (20)$$

Where: P_1, P_2 are the two parents, O_1, O_2 are two their offspring and λ_1, λ_2 are two random numbers.

3.2 Mutation

Mutation is for introducing artificial diversification in the population to avoid premature convergence to a local optimum. An arithmetic mutation operator that has proved successful in a number of studies is dynamic or non-uniform mutation. It is designed for fine-tuning aimed to achieve a high degree of precision and applied in this paper. For a given parent P, if the gene P_k is selected for mutation, then the resulting gene is selected with equal probability from the two following choices:

$$\begin{cases} O_K = P_K - r(P_K + a_k)(1 - \frac{t}{T})^b \\ O_K = P_K + r(b_k - P_K)(1 - \frac{t}{T})^b \end{cases} \quad (21)$$

Where: a_k and b_k are lower band and upper band of P_k and r is a uniform random number chosen from (0,1). t is the number of current generation ,T is the maximum number of generation and b is the parameter determining the degree of non-uniformity, that is assumed to be 3. It can be said that non-uniformity decreases as the number of generations increases [14].

3.3 Selection

In general, selection is based upon a random choosing process, where one of the selection methods is known as roulette-wheel. Individuals are mapped to the adjacent segments of a line as it is shown in Fig.6. The length of each segment on this line corresponds to the fitness value of each individual. A random number will be generated and the individual whose segment spans the random number will be selected (trial). This technique is analogous to a roulette wheel with each slice proportional in size to the fitness value [14].

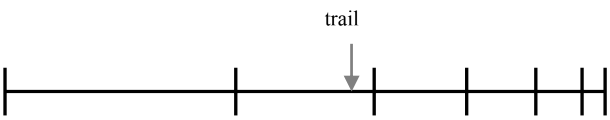

Fig.6. Roulette-Wheel selection operator

Fig. 7 illustrates the flow chart of the proposed RGA technique in this study.

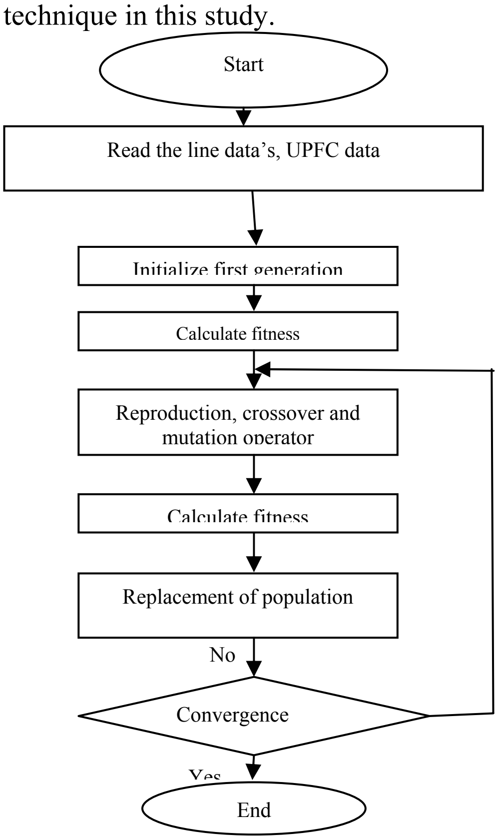

Fig.7. Real Genetic Algorithm Flow Diagram

4 Simulation Tool

In this paper, DIgSILENT commercial software is used as a simulation tool. This software has developed in 1976 in DIgSILENT Gmbh Company of Germany. Nowadays more than 80 countries use this software to simulate and implement necessary calculation in power systems. Some capabilities of this software are: power flow calculation, sensitivity analysis, contingency analysis, short circuit analysis, reliability modeling. This software is unable to determine optimal location of as well as the capacity of FACTS devices. In order to add this ability, it is modified via DIgSILENT Programming Language (DPL) module. DIgSILENT is Objective Oriented Programming (OOP), however it could support OOP facilities for users. This characteristic allows new developed software to be coded using a language similar to visual C.

5 Case Study & Results Analysis

Simulation was carried out on a modified IEEE 14-Bus system, where it is shown in Fig.8 page 6. Tables 1, 2, 3 and 4 represent; lines information, transformers data, system generation and load data respectively. Power flow study of this system shows that the voltage collapse first occurs at bus 14.

Table 1. Line Data

Line	$R_1(\Omega)$	$X_1(\Omega)$
10-11	8.205	19.207
12_13	22.092	19.988
l3_14	17.093	34.802
1-2	1.938	5.917
1-5	5.403	22.304
2-3	4.699	19.797
2-4	5.811	17.632
2-5	5.695	17.388
3-4	6.701	17.103
4-5	1.335	4.211
6-11	9.498	19.89
6-12	12.291	25.581
6-13	6.615	13.027
7-8	0	17.615
7-9	0	11.001
9-10	3.181	8.45
9-14	12.711	27.038

Table 2. Transformer Data

Transformer	Shc Volt. %	u, Magnitude HV-Side in p.u.	u, Magnitude LV-Side in p.u.
trf_4_9	20.912	0.9079347	0.9030717
trf_5_6	55.618	0.9195941	0.9354145
trf_4_7	25.202	0.9079347	0.9267493

Table 3. Load Data

Load	Active Power MW	Reactive Power Mvar	Power Factor
ld_10	14.157	9.123383	0.8405714
ld_11	5.505498	2.831394	0.8892881
ld_12	9.595295	2.516791	0.9672798
ld_13	21.23549	9.123377	0.9187929
ld_14	23.43769	7.86497	0.9480454
ld_2	34.1341	19.9771	0.8630568
ld_3	148.1766	29.88695	0.9802592
ld_4	75.18938	-6.134709	0.9966881
ld_5	11.9548	2.516798	0.9785498
ld_6	17.6176	11.79748	0.8309075
ld_9	46.40349	26.11175	0.871497

Table 4.Generation Data

Name	Bus Type	Voltage [P.U.]	Min Reactive Power Limit [Mvar]	Max Reactive .Power Limit[Mvar]
sym_8	PV	1.09	-6	24
sym_6	PV	1.07	-6	24
sym_3	PV	1.01	0	40
sym_2	PV	1.045	-40	50
sym_1_	SL	1.06	-99999	99999

In this research one UPFC is used to enhance voltage stability margin. UPFC is modeled as Steady State Injection with capacity 60 MVAr. The best location for UPFC using RGA is at line 9-14 Voltage profile is shown in Fig.9 where the voltage profile is improved significantly.

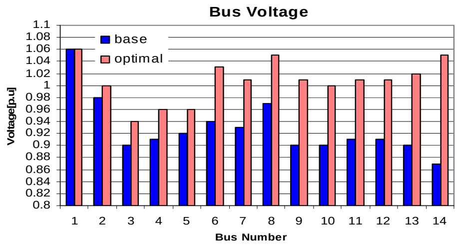

Fig.9. Voltage Profile After and Before Employing UPFC

Voltage collapse occurs at Bus14 in base case. By installation of the UPFC, voltage collapses occurs at Bus10 .PV curves for the weakest bus (Bus14) in base cases and at Bus10 in optimal case are shown in Fig.10. From this figure, it can be seen that the distance to nose point of PV curve referred to the voltage collapse point, in the presence of UPFC increased to 44.2 MW.

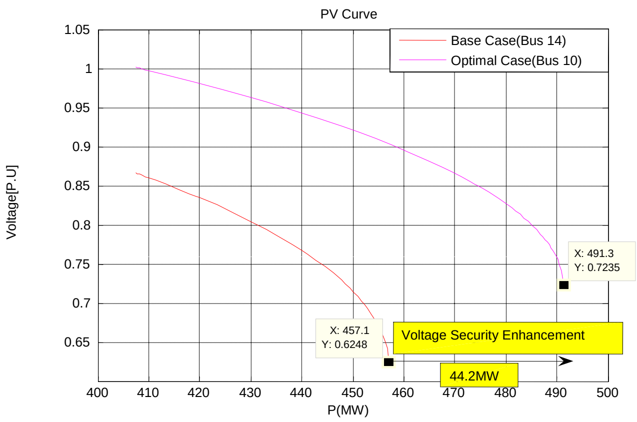

Fig.10. PV Curve at Bus 14 in Base Case & at Bus10 in Optimal Case

5.1 Cost Benefit Analysis

The benefits of using UPFC include the improvement of system dynamic behavior and thus enhancement of system reliability. However, their main function is to control power flow, voltage control and reducing active power losses. Given that UPFC is placed at optimal locations, it is capable of increasing the system loadability as well. However in deregulated environment these aspects are playing a crucial role in the operating horizon of electricity market. As long as UPFC reduces system active losses therefore the cost of such losses should be returned eventually. In this regards Table 6 represents system active losses for two cases (after and before UPFC employing) where in the presence of UPFC devices system active losses reduce to 53.67 MW.

Table 5.Modified IEEE 14 bus System Active Losses

	Base Case	Optimal Case
Losses (MW)	152.06	98.39

UPFC capital cost (installing and equipment) equals to 13.7 million$ [11]. The reduced cost of losses that is returned by using UPFC devices is calculated as 84 million$(The price of active power losses is assumed 1567 ($/kW) [15]). Saving through this trade-of can be about 70.3 million $.

6 Concluding Remarks

In this paper, a proposed RGA methodology is implemented to determine the optimal location of UPFC. It is for the aim of system voltage stability margin enhancement. Simulation results through a modified IEEE 14-bus validates the efficiency of optimal placement of UPFC. This algorithm is also effective for the optimal locating of the UPFC in the large scale power systems. Future work can be conducted on the congestion management studies. Active power losses in practical power systems can be reduced via the proposed technique.

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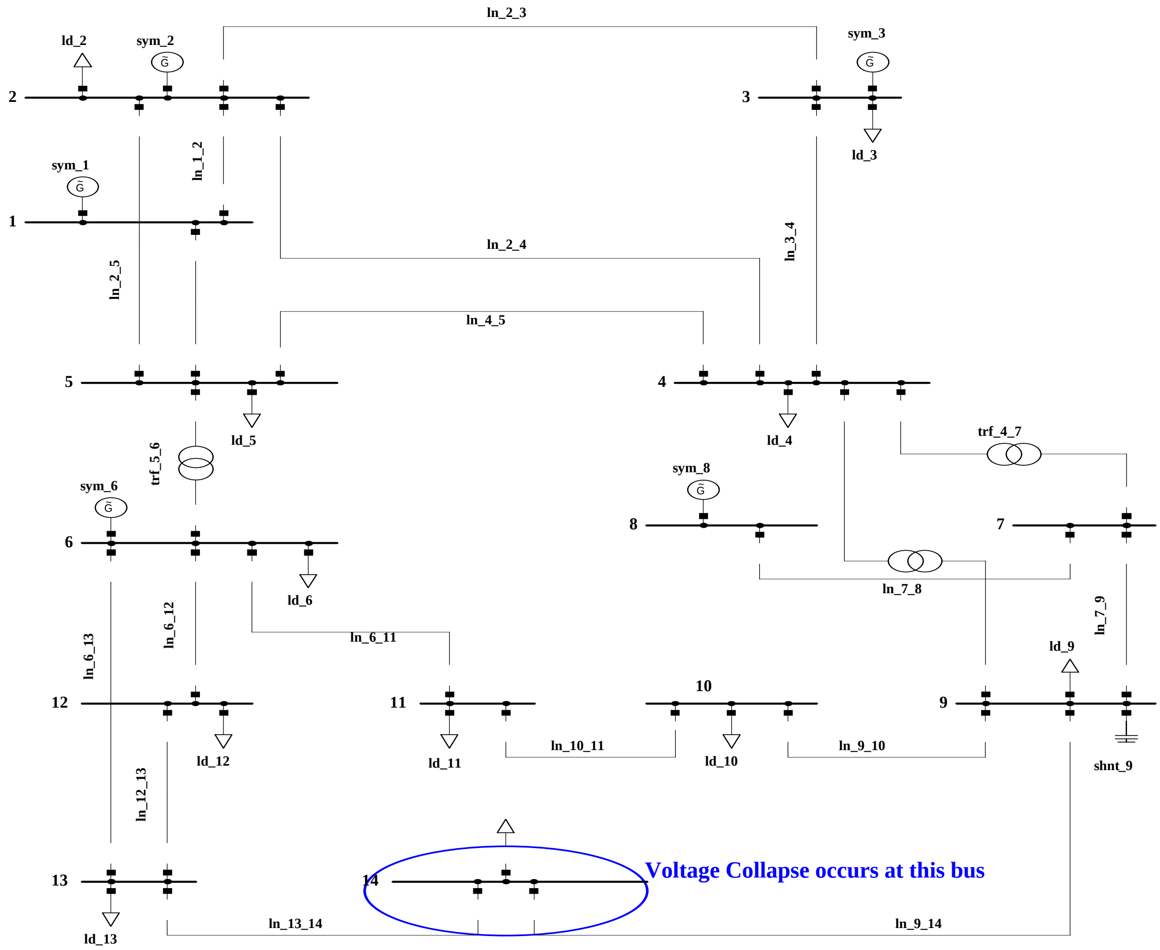

Fig8. Modified IEEE 14-Bus