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Voltage Stability Improvement Adopting Hybrid AC Microgrid on the Distribution Network: Iraq as a Case Study

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ABSTRACT

This paper, a microgrids was analyzed, designed and simulated for Holy Karbala Distribution Network by using (MATLAB 2014 a) program. Two criteria are studies in this paper toshow theeffect of applying a microgrid to the voltage stability of the system; these indexes are the L-index and Fast Voltage Stability Index (FVSI).

INTRODUCTION

Microgrids (MG) are small grouping of interconnected power generation and control technologies that can operate within or independent of a central grid and can satisfy customer requirements, such as local reliability enhancement, feeder loss reduction, local voltage regulation and increasing efficiency through the use of waste heat [1].

Holy Karbala Distribution Network:

Holy Karbala distribution network is connected to the Iraqi power grid at Al-Mussayab bus bar to the southeast of Holy Karbala city, there is another connection at Baghdad bus bar.

Holy Karbala distribution network consists of six transformers substations transform the high voltage (132 KV) to the medium voltage (33 and 11 KV). They are shown as follows:

- Three substations each substation contains three transformers of 132/33/11 KV.
- Three substations each substation contains two transformers of 132/33 KV.
- Eleven substations each substation contains two transformers of 33/11 KV.
- One substation contains three transformers of 33/11 KV.

These substations are shown diagrammatically in Figure (1), the bus data and line data of system are given in Appendix A.

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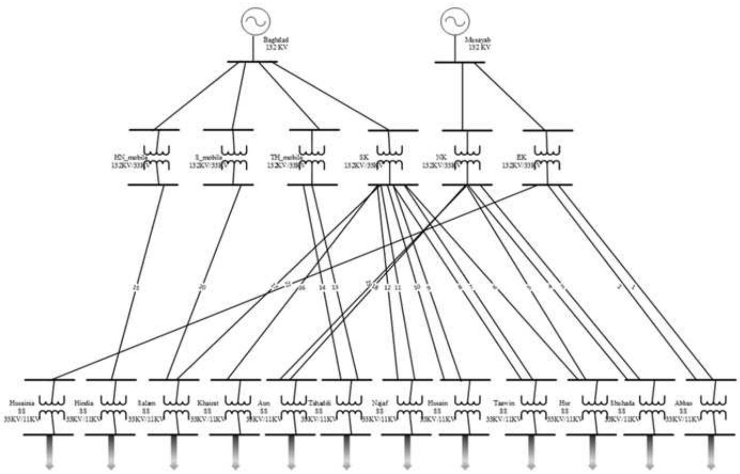

Fig. 1: Simplified diagram for Holy Karbala distribution network

Bus Voltage Stability by L-Index:
Generalization to a multi-bus system [2]:

From the basic theory of multi-bus power system, all the buses can be divided into two categories: Generator bus (PV bus and Slack bus) and Load bus (PQ bus). Because the voltage stability problem is reactive power relative problem, and the generator bus can provide the reactive power to support the voltage magnitude of the bus, it is absolutely necessary that buses should be distinguished.

We can use the Kirchhoff Current Law to express the circuit of N-bus system:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \tag{1}$$

Here the subscripts L and G denote load buses and generator buses, respectively.

Equation (1) can be expressed in the hybrid form:

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & K_{LG} \\ F_{GL} & M_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} = [H] \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{2}$$

Where Z_{LL} ,K_{LG} ,F_{GL} ,M_{GG} are Sub matrices of the hybrid matrix (H-matrix)

Actually, the sub matrix Z_{LL}or K_{LG} is the most important part in the L index derivation.

where:

$$Z_{LL} = Y_{LL}^{-1}$$

When we consider the voltage at load bus j, we use the following equation:

$$\overline{V}_j = \sum_{i \in L} \overline{Z}_{ji} \overline{I}_i + \sum_{k \in G} \overline{K}_{jk} \overline{V}_k$$

Which can be expressed as follows:

$$\overline{V}_j - \sum_{k \in G} \overline{K}_{jk} \overline{V}_k = \sum_{i \in L} \overline{Z}_{ji} \overline{I}_i$$

Multiplying by V_j^*; at both sides of the above equation:

$$V_j^2 + V_j^* \overline{V}_{oj} = V_j^* \sum_{i \in L} \overline{Z}_{ji} \overline{I}_i \tag{3}$$

Where;

$$\overline{V}_{oj} = -\sum_{k \in G} \overline{K}_{jk} \overline{V}_k$$

The term$\overline{V}_{oj}$ is representative of an equivalent generator comprising the contribution from all generators.

Expanding the j term in equation (3), we get:

$$V_j^2 + V_j^* \overline{V}_{oj} = V_j^* (\overline{Z}_{jj} \overline{I}_j + \sum_{\substack{i \in L \\ i \neq j}} \overline{Z}_{ji} \frac{S_i^*}{V_i^*})$$

$$V_j^2 + V_j^* \overline{V}_{oj} = V_j^* \overline{I}_j \overline{Z}_{jj} + \sum_{\substack{i \in L \\ i \neq j}} \overline{Z}_{ji} \frac{S_i^*}{V_i^*} V_j^*$$

$$V_j^2 + V_j^* \overline{V}_{oj} = S_j^* \overline{Z}_{jj} + \overline{Z}_{jj} \sum_{\substack{i \in L \\ i \neq j}} \frac{\overline{Z}_{ji}}{\overline{Z}_{jj}} \frac{S_i^*}{V_i^*} V_j^*$$

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$$V_j^2 + V_j^* \overline{V}_{oj} = \overline{Z}_{jj}(S_j^* + \sum_{\substack{i \in L \\ i \neq j}} \frac{\overline{Z}_{ji}}{\overline{Z}_{jj}} \frac{S_i^*}{V_i^*} V_j^*)$$
$$V_j^2 + V_j^* \overline{V}_{oj} = \overline{Z}_{jj}\left(S_j^* + S_{j+}^*\right)$$
$$V_j^2 + V_j^* \overline{V}_{oj} = \overline{Z}_{jj} * S_{jtot}^* \quad (4)$$

where
$$S_{j+}^* = \sum_{\substack{i \in L \\ i \neq j}} \frac{\overline{Z}_{ji}}{\overline{Z}_{jj}} \frac{S_i^*}{V_i^*} V_j^*$$

S_{j+}^*represents the 'contributions' of the other load buses, while S_j^* represents the load at bus j itself.

$\overline{Z}_{ji}$: the element of sub matrix Z_{LL} at the ith load bus that is connected to the load bus j.

$\overline{Z}_{jj}$: the element of sub matrix Z_{LL} at the load bus j.

Hence, rearranging equation (4), we get:
$$V_j^2 + V_j^* \overline{V}_{oj} = \frac{S_{jtot}^*}{\overline{Y}_{jj}} \quad (5)$$
where : $\overline{Y}_{jj} = \overline{Z}_{jj}^{-1}$

From the previous analysis, we know that:
$$L_j = \left|1 + \frac{\overline{V}_{0j}}{\overline{V}_j}\right| = \left|\frac{S_{jtot}^*}{V_j^2 * \overline{Y}_{jj}}\right| = \frac{S_{jtot}}{V_j^2 * Y_{jj}} \quad (6)$$

From equation (4), it is clear that the L index of the voltage stability at a load bus is mainly influenced by the equivalent load S_{jtot}^* , which has two parts: the load at bus j itself S_j^* , and the 'contributions' of the other load busesS_{j+}^***.** When the load at a load bus changes, it will influence the L index.

For the system, the vulnerable load bus must have the maximum L index value.

Index **system** = Max(Index **j) ,** where j ϵ L

From the derivation, it is seen that for computing the L index, at any load bus, one requires only the knowledge of the power flow information and the network topology, which can be obtained very quickly in real-time.

The procedure for voltage stability L index programming is summarized below:

1. Initialize active and reactive load power of the load bus which has to be tested, where two variables are used for this purpose, such as P_L and Q_L.
2. Define power system base MVA, power mismatch accuracy, acceleration factor and maximum number of iterations.
3. Enter bus data, line data of the electrical network .
4. The load flow solution is performed using NR power flow .
5. The resulting complex load bus voltages for all load buses are saved.
6. If the iterative solution converges, the active and reactive load power are increased with constant power factor. The increment can be expressed as ΔP_L for active power and ΔQ_L for reactive power. Then, steps 3 and 4 are repeated until the iterative solution diverges.
7. The sub-matrix Z_{LL} is formed by inverting the sub-matrixY_{LL}.Y_{LL}represents the admittances that connect the load buses with each other, which can be obtained easily from the Y-matrix of the network.
8. Extract the terms corresponding to the specified load bus (bus j) from the sub-matrix Z_{LL}. Then, calculate S_{jtot}^* from the following equation:
$$S_{jtot}^* = S_j^* + \sum_{\substack{i \in L \\ i \neq j}} \frac{\overline{Z}_{ji}}{\overline{Z}_{jj}} \frac{S_i^*}{V_i^*} V_j^* \quad (7)$$
9. The L index of (bus j) is calculated from the following equation:
$$L_j = \left|\frac{S_{jtot}^*}{V_j^2 * \overline{Y}_{jj}}\right| \quad (8)$$

Fast Voltage Stability Index (FVSI)[3]:

This index can either be referred to a bus or a line. The voltage stability index developed in this work is referred to a line. Generally, it is started with the current equation to form the power or voltage quadratic equations.

The criterion employed in this work was to set the discriminant of the roots of voltage or power quadratic equation to be greater than zero.

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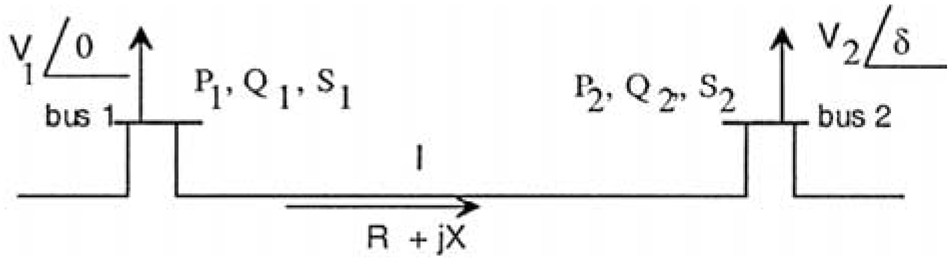
When the discriminant is less than zero, it causes the roots of the quadratic equations to be imaginary which in turn cause voltage instability in the system. The line index that is evaluated close to 1 will indicate the limit of voltage instability.



V_1, V_2 =Voltage on sending and receiving buses
P_1, Q_1 = active and reactive power on the sending bus
P_2, Q_2 = active and reactive power on the receiving bus
S_1, S_2 = apparent power on the sending and receiving buses
$\delta = \delta_1 - \delta_2$ (angle difference between sending and receiving buses)
The line impedance is noted as Z = R+jX with the current (I) that flows in the line given by;

$$I = \frac{V_1\angle\theta - V_2\angle\delta}{R+jX} \quad (9)$$

V_1 is taken as the reference and therefore the angle is shifted to 0.
The apparent power at bus 2 can be written as;

$$S_2 = V_2 I^* \quad (10)$$

Rearranging the Equation (10) yields;

$$I = \left(\frac{S_2}{V_2}\right)^* \quad (11)$$

$$= \frac{P_2 - jQ_2}{V_2\angle-\delta} \quad (12)$$

Equating Equations (9) and (12),

$$\frac{V_1\angle\theta - V_2\angle\delta}{R+jX} = \frac{P_2 - jQ_2}{V_2\angle-\delta}$$

$$V_1V_2\angle-\delta - V_2^2\angle 0 = (R+jX)(P_2 - jQ_2) \quad (13)$$

Separating the real and imaginary parts yields,

$$V_1V_2\cos\delta - V_2^2 = RP_2 + XQ_2 \quad (14)$$

And,

$$-V_1V_2\sin\delta - V_2^2 = XP_2 - RQ_2 \quad (15)$$

Rearranging Equation (14) for P_2 and substituting into equation (13) yields a quadratic equation of V_2;

$$V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \quad (16)$$

The roots for V_2 will be;

$$V_2 = \frac{\frac{R}{X}\sin\delta + \cos\delta \pm \sqrt{\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2}}{2} \quad (17)$$

To obtain real roots for V_2, the discriminant is set greater than or equal to 0;

$$\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0$$

$$\frac{4Z^2Q_2X}{(V_1)^2(R\sin\delta + X\cos\delta)^2} \leq 1 \quad (18)$$

Since δ is normally very small then
$\delta \approx 0$, $R\sin\delta \approx 0$ and $X\cos\delta \approx X$

Taking the symbols 'i' as the sending bus and 'j' as the receiving bus, the Fast Voltage Stability Index (FVSI) can be written as follows;

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X_{ij}} \quad (19)$$

Where,
Z = line impedance
X_{ij} = line reactance

Q_j = reactive power at the receiving end
V_i = sending end voltage
The value of FVSI that is evaluated close to 1 indicates that the particular line is close to its instability point which may lead to voltage collapse in the entire system. To maintain a secure condition the value of FVSI should be maintained well less than 1.

5. Voltage Stability Improvement Results:

Two criteria adopted in this work for voltage stability improvement as below:

A. Bus bar voltage stability:

L- Index is adopted to show the voltage stability improvement on the bus bar. Table (1) shows the effect of adopting microgrid strategy on the bus bar stability.

Table 1: L-Index

Substation	L-Index without MG.	L-Index with MG.
Al-Hindia	0.0348	0.00777
Al-Hussainia	0.372	0.14515

Its clear that using of micrograds lead to decrease L-Index which indicates that it increase the voltage stability on the bus bar.

B. Line voltage stability:

Fast Voltage Stability Index (FVSI) is adopted to show line voltage stability improvement. Table (2) shows the effect of adopting microgrid strategy on the line stability.

Table 2: FVSI Index

Line no.	Line location	FVSI without MG.	FVSI with MG.
15	Al-Hindia mobile-Al-Hindia SS	0.1463	0.0699
21	East Karbala-Al-Hussainia SS	0.7364	0.4717

From table (2), its clear that using of micrograds lead to decrease FVSI index which indicates that it increase the voltage stability on the line.

Conclusions:

From the results above its clear that using of microgrids lead to decrease L-Index which indicates that it increase the voltage stability on the bus bar and also it lead to decrease FVSI index which indicates that it increase the voltage stability on the line.

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Appendix A:

Data Base of Holy Karbala distribution system

Table A.1: Bus data of Holy Karbala distribution system

Bus NO.	Station Name	V P.U.	δ Degree	P_L MW	Q_L Mvar
1	East Karbala	1	0	0	0
2	North Karbala	-	-	0	0
3	South Karbala	-	-	0	0
4	Al-Tahaddy mobile	-	-	0	0
5	Al-Salam mobile	-	-	0	0

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6	Al-Hindia mobile	-	-	0	0
7	Abbas SS	-	-	34.8	16.85
8	Shuhadaa SS	-	-	44.4	13.3
9	Al-Hur SS	-	-	13.3	6.483
10	Al-Taawin SS	-	-	29.1	14.065
11	Al-Hussain SS	-	-	23.1	11.165
12	Al-Najaf SS	-	-	34.3	16.578
13	Al-Tahaddy SS	-	-	32.2	16.563
14	Al-Hindia SS	-	-	43.08	20.822
15	Khairat SS	-	-	21.3	10.295
16	Al-Salam SS	-	-	41.8	20.203
17	Aun SS	-	-	23.33	11.271
18	Al-Hussainia SS	-	-	31.3	15.128

Table A.2: Line data of Holy Karbala distribution system

Line No.	From Bus	To Bus	R (P.U)	X (P.U)
1	1	7	1.205	3.146
2	1	7	1.405	3.668
3	2	8	1.147	2.996
4	2	8	0.557	1.455
5	2	9	0.451	1.178
6	3	9	0.874	2.282
7	3	10	0.436	1.138
8	3	10	0.436	1.138
9	3	11	0.195	0.511
10	3	11	0.195	0.510
11	3	12	0.354	0.925
12	3	12	0.355	0.927
13	4	13	0.130	0.340
14	4	13	0.131	0.341
15	6	14	0.058	0.153
16	3	15	0.261	0.683
17	5	16	0.503	1.315
18	3	16	0.505	1.320
19	2	17	0.212	0.554
20	2	17	0.212	0.554
21	1	18	1.175	3.066