

Loadability Assessment and Enhancement in Unbalanced Distribution Systems

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Abstract—Voltage stability is a major concern in heavily loaded distribution networks. Careful determination of control parameters for loadability enhancement may maximize the utilization of distribution networks. In applicable studies, most of the approaches optimize real/reactive power losses for the current operating conditions of the distribution network. Although, these types of approaches increase the stability margin, such an increase may not be sufficient. The most important factor in loadability enhancement is representation of future load scenarios in addressing the optimization problem. In this paper a look ahead approach is developed for loadability enhancement of an unbalanced distribution system. The determination of the critical loading point is conventionally done using continuation power flow, which is computationally very demanding, and also complex for implementation in unbalanced distribution networks. Therefore, a new, computationally very efficient voltage stability indicator is developed here for determination of the loadability limit. The proposed methodology is demonstrated on IEEE 4 bus and 25 bus unbalanced distribution systems with different transformer connections.

Index Terms—loading, stability margin, voltage stability indicator, unbalanced power flow.

I. INTRODUCTION

DUE to the increase in electricity demand during peak hours, power systems in many countries are forced to operate with low voltage stability margins. With the stressed operation of distribution networks, voltage stability becomes a challenging constraint in both the operational as well as planning aspects. The introduction of open competition among various utilities leads to congested networks at times, which further adds to the stability problems. In a strong power system, voltage limits should be rigid. From time to time, voltage stability studies have always gained attention in research studies. A brief review of applicable literature covering these studies is presented below.

Jasmon et al. [1] and Gubina et al. [2] discussed the voltage stability analysis of radial networks by representing the whole network as an equivalent single line network. Chakravorty et al. [3] proposed an indicator derived from distribution system

load flow. But it requires a large computational effort as it solves fourth order equations. Chen et al. [4] proposed a sensitivity matrix based indicator and Alonso et al. [5] presented a genetic algorithm based methodology to find the voltage stability in a distributed generator environment.

Power systems attain a state of voltage instability due to an increase in load, a large disturbance, lack of reactive compensation or unsuitable location of compensating devices. The voltage stability issues can lead to serious blackouts in a system. The voltage stability can be enhanced by proper scheduling of control parameters such as taps on transformers and shunts.

Toma et al. [6] proposed a voltage control methodology by using tap changing transformers. In this study, changing the taps according to voltage variations on the secondary side of the transformer controls the voltage. A tap is changed if the voltage moves away from a range between $\pm 1.25\%$. Liu et al. [7] developed a nonlinear interior-point method for voltage control in distribution systems by optimizing the tap setting of the transformer, the number of switching operations of the transformer LTC and the capacitors.

Shunt capacitors are also used in voltage regulation of distribution systems. The capacitor banks can be represented as susceptances connected in either star or delta. The shunt capacitors can also be modeled as equivalent current injections [8], [9]. The current injection model of shunt capacitors can be easily included in backward/forward power flow processes.

The determination of loadability limits is the first task while attempting steady state voltage stability analysis and enhancement. This is conventionally done with continuation power flow (CPF). Though CPF has been proved to be the most accurate, it is computationally very demanding. In case of unbalanced distribution networks, it is very complex to implement. In some cases, the power flow Jacobian matrix is ill conditioned and a solution is not possible.

For quick and computationally cheaper calculations of voltage stability limits, many voltage stability indices have been proposed in applicable literature. But, most of the discussions are only done for balanced distribution networks. Thus, it is seen from the applicable literature that because of the special structure and features of the distribution system, blind extension of approaches suitable for transmission systems does not always work well.

Therefore, the first objective of this paper is to develop new, simple voltage stability indices for radial distribution networks.

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The developed indices are based on the percentage change in losses, and voltages, with an increase in loading. These indices are independent of the type of power flow analysis used. Therefore, a well-proven, three-phase forward backward power flow algorithm is utilized for evaluation. Comparison of results is done using a conventional CPF to prove the accuracy of developed indices. Representation of future load scenarios is crucial to the success of any optimization technique. A look ahead approach is developed for voltage stability enhancement. This type of approach facilitates the rescheduling of control variables for maximizing the loadability margin, and looking at present and future operating conditions. Section II describes the framework for the look ahead approach and details the three-phase unbalanced power flow method. The mathematical modeling of voltage stability indices is explained in section III.

Section IV presents the mathematical model and algorithm for optimization. Taps of the transformers and shunts are taken as control variables. An improved harmony search algorithm is utilized for optimization. Section V presents the results and discussions. This study is concluded in Section VI.

II. FRAMEWORK FOR LOOK AHEAD APPROACH

In general, the real/reactive power optimization is carried out at the present loading, and the control variables are rescheduled as per these requirements. In particular, reactive power controls are scheduled for minimizing the real or reactive power losses.

As mentioned earlier, there are many instances where power systems are forced to operate near their network loadability limits. In such a situation, close monitoring of the distance to collapse, and its enhancement becomes critical for power system operators. Also, the system behavior is quite nonlinear around the critical loading point. Therefore, the early obtaining of reactive resources (or increase in reactive margins) may help in delaying this situation. For this to occur, it becomes of utmost importance to represent load increase scenarios in the optimization process in some fashion and schedule the controls in an adaptive manner. In a one-step look ahead formulation, at each operating condition, the next load increase is predicted (forecasted). In this approach, at every load step the real power loss is optimized. It can then be checked with these controls to determine whether meeting the next load step (from forecasting) is possible or not. If the load can be met at the next load step, one resorts to the present load based optimization. However, if the next load step is infeasible with the present setting of the controls, then this optimization is not sufficient and the real power losses are optimized by meeting the constraints for both the operating conditions. The complete framework can be depicted as shown in Fig. 1.

A backward/forward power flow process that identifies the current in each branch based on the Kirchhoff current law and also the voltage at each bus based on the Kirchhoff voltage law is reported in [10]–[13]. This paper utilizes a backward/forward process of unbalanced distribution power flow [13]. The detailed process of the power flow analysis is given in Appendix C.

The value of the transformer admittance matrix is determined based on three sub matrices, and [14]. Moreover, in

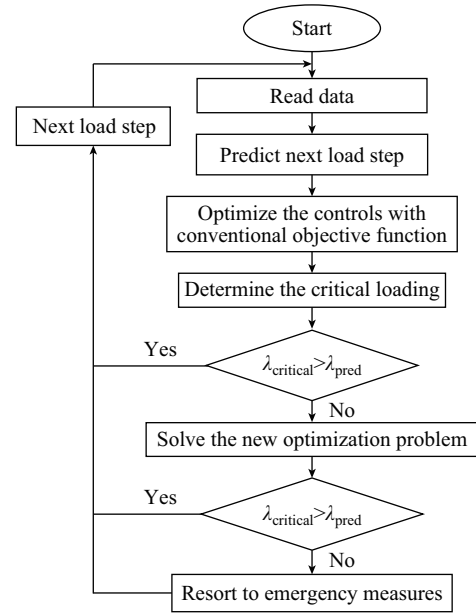


Fig. 1. Look-ahead approach.

the backward and forward step process, the secondary current and primary voltage are modernized as in [15] to avoid the singularity problem of the transformer solution.

III. NEW VOLTAGE STABILITY INDICES

Operators and analysts have observed that as the load increases, the bus voltages drop, and the system loss increases. Although, these changes are nonlinear, there is nothing abnormal about these when the actual loading is not near the critical loading. However, as we approach the critical loading, the voltage drop at the weakest bus, and the power loss in the most stressed line, increases abnormally. The proposed indices are designed to detect such a condition.

A. Voltage Based Stability Indicator

Voltage based stability indicators can be defined as the percentage change in the voltage at every bus in two consecutive load steps. The percentage change in voltage at phase p ($p = a, b, c$) of the i^{th} bus will be:

$$PCV_{ip} = \frac{V_{ip}^{\lambda^n} - V_{ip}^{\lambda^{n-1}}}{V_{ip}^{\lambda^n}} \times 100 \quad (1)$$

where λ^{n-1} and λ^n are the previous and current loading factors. $V_{ip}^{\lambda^{n-1}}$ and $V_{ip}^{\lambda^n}$ are the voltages in a particular phase p corresponding to previous and current loading.

The voltage based stability indicator is given by (2):

$$VSI_{V_{ip}} = (PCV_{ip})^2 / 100 \quad (2)$$

where PCV_{ip} is the percentage change in voltage at phase p ($p = a, b, c$) of the i^{th} bus.

B. Loss Based Stability Indicator

The loss based stability indicator is based on the percentage change in the active power loss of each line in two consecutive

loading steps. The change by percentage in active power losses in the l^{th} line (phase p) can be written as:

$$PC_{PL_{lp}} = \frac{PL_{lp}^{\lambda^n} - PL_{lp}^{\lambda^{n-1}}}{PL_{lp}^{\lambda^n}} \times 100 \quad (3)$$

where λ^{n-1} and λ^n are the previous and current loading factors. $PL_{lp}^{\lambda^{n-1}}$ and $PL_{lp}^{\lambda^n}$ are the active power losses in a particular phase p of the l^{th} line corresponding to the previous and current loading.

The loss based stability indicator is represented as:

$$VSI_{PL_{lp}} = (PC_{PL_{lp}})^2 / 100 \quad (4)$$

where $PC_{PL_{lp}}$ is the percentage change in active power losses in the l^{th} line (phase p). The major benefit of these indices is their availability almost without any additional computational cost, and also any power flow method can be utilized.

IV. OPTIMIZATION METHODOLOGY

A. Objective Function

Four types of objective functions are considered in this study as follows:

1) Minimizing Active Power Loss

$$Obj_{P_{\text{loss}}} = \min \left(\sum_{l=1}^{NL} \sum_{ph=a,b,c} P_{\text{loss}_l}^{\text{ph}} \right) \quad (5)$$

where $P_{\text{loss}_l}^{\text{ph}}$ is the active power loss of the ph phase of the l^{th} line. NL is the total number of the line and ph is the number of phases.

The set of equality and inequality constraints which need to be satisfied are as follows:

Equality Constraint:

- The equality constraint is the power balance i.e. total power injected at a bus should be equal to the difference of total generation and demand at that bus.

$$P_i^G - P_i^D = V_i \sum_{j=1}^n V_j (g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij}) \quad (6)$$

where P_i^G is the total power generation and P_i^D is the total power demand. g_{ij} and b_{ij} are the real and imaginary part of the $(i,j)^{\text{th}}$ entity of the bus admittance matrix. As this study is carried out on a distribution system, there is only one generation system which is a substation.

Inequality constraints:

- The voltage should be within allowable limits. If V_i^{ph} is the voltage of the i^{th} bus (phase ph), and V_i^{min} and V_i^{max} are the minimum and maximum limits of voltages, then:

$$V_i^{\text{min}} \leq V_i^{\text{ph}} \leq V_i^{\text{max}}, \text{ where } ph \in abc \quad (7)$$

- The control variable, and shunts should be selected within the permissible limit. If Sh_j is the value of the j^{th} shunt, and Sh_j^{min} and Sh_j^{max} are the minimum and maximum limits of the shunts, then:

$$Sh_j^{\text{min}} \leq Sh_j \leq Sh_j^{\text{max}} \quad (8)$$

- Transformer taps setting should be within available range.

$$Tap_k^{\text{min}} \leq Tap_k \leq Tap_k^{\text{max}} \quad (9)$$

where Tap_k is the tap setting of the k^{th} transformer and Tap_k^{min} and Tap_k^{max} are the minimum and maximum limits of transformer taps.

2) Minimizing Reactive Power Loss

$$Obj_{Q_{\text{loss}}} = \min \left(\sum_{l=1}^{NL} \sum_{ph=a,b,c} Q_{\text{loss}_l}^{\text{ph}} \right) \quad (10)$$

where $Q_{\text{loss}_l}^{\text{ph}}$ is the reactive power loss of the l^{th} line (phase ph), and is subject to the constraints as described within the previous objective, equations 6 to 9.

3) Maximizing the Voltage Stability Indicator

Maximizing the voltage stability indicator, whenever the value of the next indicator is less than double that of the present indicator. This is achieved by, maximizing the differences of two successive voltage stability indicators (VSI) up to the critical loading point, i.e., we are maximizing the critical loading point in an indirect way.

$$Obj_{VSI} = \max \left(\max \left(\left(VSI_i^{\text{ph}} \right)^{n+1} - \left(VSI_i^{\text{ph}} \right)^n \right) \right), \quad ph \in a, b, c \text{ and } i = 1 \dots NB \quad (11)$$

Subject to the constraints (6-9) and one additional constraint as:

$$\left(\max \left(VSI_i^{\text{ph}} \right) \right)^{n+1} < 2 \times \left(\max \left(VSI_i^{\text{ph}} \right) \right)^n \quad (12)$$

where NB is the total number of buses. n and $n+1$ indicates the present and next loading states and “2” reflects the unexpected change in VSI, and the phenomena indicates the voltage collapse point, as observed in Section V (A).

4) Active Power Loss Minimization with VSI as the Constraint

$$Obj_{(P_{\text{loss}}, VSI)} = \min \left(\sum_{l=1}^{NL} \sum_{ph=a,b,c} P_{\text{loss}_l}^{\text{ph}} \right) \quad (13)$$

The active power loss (13) is minimized with constraints in (6-9) and an additional constraint of the voltage stability indicator as shown in (12). In this model, the VSI is considered as a constraint in the optimization processes to ensure the stability of the system for the available controls setting.

B. Look-ahead Approach

In this process, the objective functions are considered in two different ways for optimization [16]. First is the minimization of the considered objective at the present operating condition and second is near the critical loading point.

The look ahead optimization is carried out in this paper considering four different objective functions (5, 10, 11 and 13) to present a comprehensive analysis and applicability of the developed approach. The mathematical models for both cases using the objective function given by (5) are presented in the following sub sections. For the other three objectives,

the equality and inequality constraints remain the same as explained in Section IV (A).

1) *Minimization of Total Active Power Loss at the Present Loading*: This is the conventional present loading optimization. In this scenario, the total active power losses in the lines are considered for optimization which can be represented as:

$$Obj = \min \left(\sum_{l=1}^{NL} \sum_{ph=a,b,c} P_{loss_{ph}}(l) \right) \quad (14)$$

Subjected to

Equality constraint:

$$P_i^G - P_i^D = V_i \sum_{j=1}^n V_j (g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij}) \quad (15)$$

Inequality constraints:

$$V_i^{\min} \leq V_{ia} \leq V_i^{\max} \quad (16)$$

$$V_i^{\min} \leq V_{ib} \leq V_i^{\max} \quad (17)$$

$$V_i^{\min} \leq V_{ic} \leq V_i^{\max} \quad (18)$$

$$U_k^{\min} \leq U_k \leq U_k^{\max} \quad (19)$$

where Obj is the objective function to be minimized at the present loading conditions. NL is the total number of lines in the system, ph is the number of phases, P_i^G , P_i^D and P_i are power generation, demand and net injection at i^{th} bus, $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum limit on the i^{th} bus voltage. V_{ia} is the i^{th} bus (phase a) voltage at present loading, $U_k^{\min}$ and $U_k^{\max}$ are the minimum and maximum limits on the k^{th} control variable. And (15) represents the present loading and power balance constraint.

2) *Minimization of Total Active Power Loss Near Critical Loading*: This is the new (look-ahead) optimization proposed especially for loadability enhancement. The objective is the minimization of the sum of series active power losses in the lines with voltage and control variable constraints at present (predicted) and previous operating conditions determined as:

$$Obj^C = \min \left(\sum_{l=1}^{NL} \sum_{ph=a,b,c} P_{Loss_{ph}}^C(l) \right) \quad (20)$$

Subjected to:

$$P_i^G - P_i^D = V_i \sum_{j=1}^n V_j (g_{ij} \cos \theta_{ij} + b_{ij} \sin \theta_{ij}) \quad (21)$$

$$V_i^{\min} \leq V_{ia}^p \leq V_i^{\max} \quad (22)$$

$$V_i^{\min} \leq V_{ib}^p \leq V_i^{\max} \quad (23)$$

$$V_i^{\min} \leq V_{ic}^p \leq V_i^{\max} \quad (24)$$

$$V_i^{\min} \leq V_{ia}^C \leq V_i^{\max} \quad (25)$$

$$V_i^{\min} \leq V_{ib}^C \leq V_i^{\max} \quad (26)$$

$$V_i^{\min} \leq V_{ic}^C \leq V_i^{\max} \quad (27)$$

$$U_k^{\min} \leq U_k \leq U_k^{\max} \quad (28)$$

where Obj^C is the objective function near the critical loading point. V_{ia}^p is the i^{th} bus (phase a) voltage at present loading, and V_{ia}^C is phase a voltage of the i^{th} bus evaluated near the critical loading point.

C. Improved Harmony Search Algorithm

In this problem, controls are varying in discrete steps, so a meta-heuristic technique will be more feasible for the optimization process. The control variables are optimized using an improved harmony search algorithm (IHS). Z. W. Geem *et al.* [17] introduced a new meta-heuristic algorithm named Harmony Search (HS) that is phenomenon conceptualized using a mimicking musical process of searching for a perfect state of harmony. Pandi *et al.* [18], [19] proposed that if BW is the standard deviation of the population in each improvisation; it has better explorative power in the improved harmony search algorithm. Therefore, this version of IHS is utilized in the present study. Fig. 2 describes the steps of the improved harmony search algorithm. To check the value of each solution, fitness function FF is evaluated as the sum of the objective function and the penalties on the constraint violations.

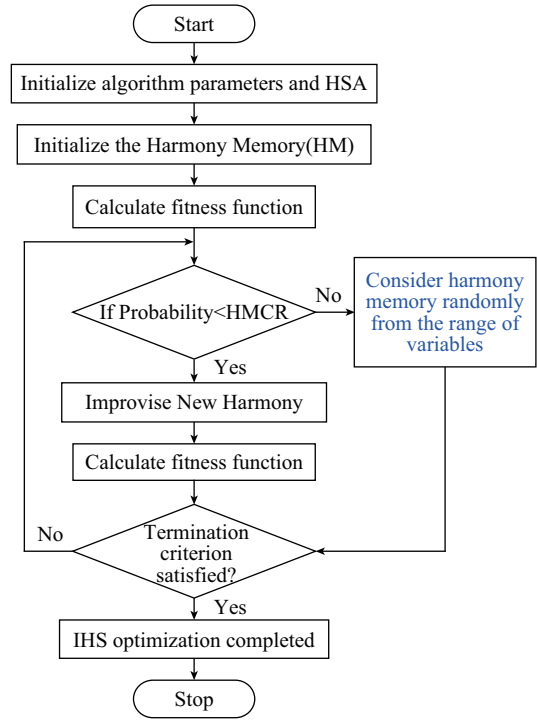


Fig. 2. Flow chart of improved harmony search algorithm.

The IHS is utilized as the optimization algorithm in this paper for demonstration purposes, however, the approach is general enough and any other algorithm can also be utilized. The steps for the Look-ahead approach are as follows:

Step 1: Run load flow.

Step 2: Optimize the controls with the objective as total active power loss minimization using the IHS method.

Step 3: With these optimized controls, calculate the critical loading point (λ_c) using the voltage stability indicator (2).

Step 4: Predict the next loading step (λ_p) by load forecasting.

Step 5: Check

- i. If $\lambda_c > \lambda_p$, go to Step 2 and optimize the control at $\lambda = \lambda_p$.
- ii. If $\lambda_c < \lambda_p$, set marginal loading point (λ_m) just below

λ_c (i.e. near the critical loading point) the critical loading point)

Step 6: At this λ_m , optimize the controls with the objective function meeting the constraints at both the operating points (λ_m and λ) with controls at the λ_m IHS method.

Step 7: With these new controls, calculate the new critical loading point (λ_c^m) using the voltage stability indicator (2).

Step 8: Check

- i. If $\lambda_c^m > \lambda_p$, go to Step 2 and optimize the controls at $\lambda = \lambda_p$.
- ii. If $\lambda_c^m < \lambda_p$, be ready for an emergency.

V. RESULTS AND DISCUSSION

A. Voltage stability indicator of IEEE 4-Bus System

An IEEE 4 bus system consists of 4 buses and one transformer between bus 2 and 3. The base case load flow results are also validated with [20] and ETAP power flow solutions.

Comparing the results for the above system for balanced and unbalanced test cases, validate the proposed voltage stability indices with the ones given in [21]. In [21], Araujo et al. have developed a three phase continuation power flow. The results obtained for different types of transformer connections are shown in Table I, where PI_{mlp} is the increase by percentage of the Maximum Loading Point, it is shown as to compare the results of proposed methodology in [21] to demonstrate the adequacy of proposed methodology in this paper.

TABLE I
THREE-PHASE STEP DOWN TRANSFORMER CONNECTION SUBMATRICES

Case	Type of Transformer connection	Type of Load	PI_{mlp}	
			By [21]	Proposed Method
1	$Y_g - Y_g$	Balanced	33.1%	33%
2	$Y_g - Y_g$	Unbalanced	13.2%	13%
3	$\Delta - Y_g$	Balanced	34.8%	32%
4	$\Delta - Y_g$	Unbalanced	14.9%	15%

The maximum variation of voltage and loss based VSI with the increase in system load for the balanced case is shown in Fig. 3 and Fig. 4 respectively. From Fig. 3 and Fig. 4 it can be observed that at the critical loading point there is a steep change in the voltage or loss profile that gives a clear indication of the maximum loading point. That steepness could be at any of the bus or line points according to its weakness. In the present case for the voltage based VSI, the maximum steepness is in the phase a voltage of bus 4 and phase b

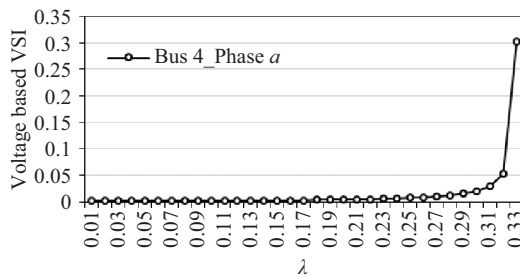


Fig. 3. Voltage based VSI of IEEE 4-bus Y_g-Y_g balanced case at bus 4 (phase a).

of line 3 for the power based stability indicator. Since both indices shows similar results, the voltage based VSI is further utilized in the optimization process.

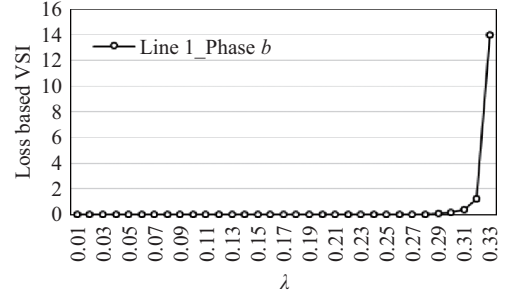


Fig. 4. Loss based VSI of IEEE 4-bus Y_g-Y_g balanced case at line 1 (phase b).

Fig. 5 and Fig. 6 show the voltage profile of the balanced and unbalanced cases at different buses. It can be observed from the figures that in the balanced case, the voltage of phase a is decreasing, while the phase b and c voltage shows increasing behavior up to the maximum loading point. In the unbalanced case, phase c has the lowest voltage because of the highest load connected to that phase. Similarly, the voltage profiles for balanced and unbalanced cases are shown in Fig. 7 and Fig. 8 respectively, which are exactly matching with the ones reported in [21].

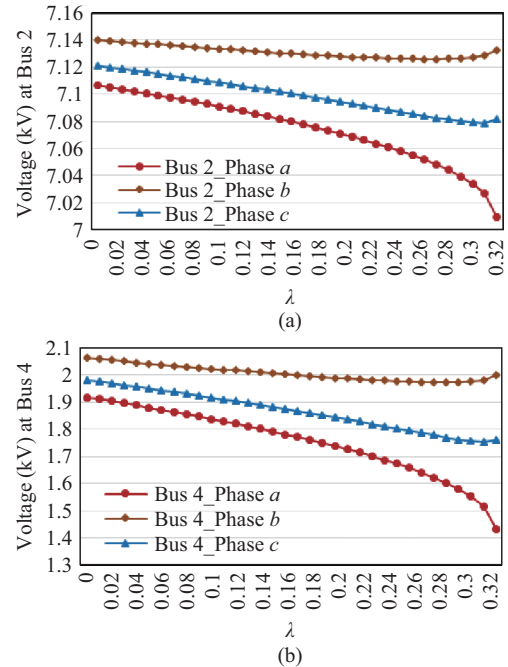


Fig. 5. Voltage profile of IEEE 4-bus Y_g-Y_g balanced case. (a) Voltage at bus 2. (b) Voltage at bus 4.

B. Look-ahead Approach

The loadability enhancement with look ahead approach is attempted for standard 10-bus balanced [22], 52-bus practical distribution system [23] and IEEE 4-bus and modified 25-bus [24], [25] unbalanced distribution systems.

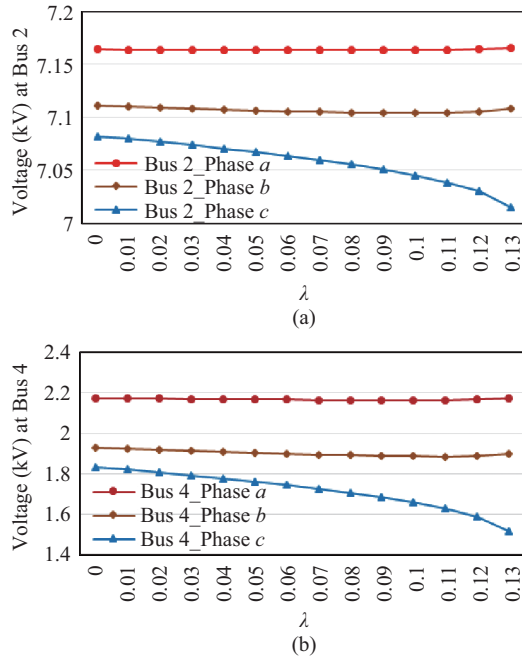


Fig. 6. Voltage profile of IEEE 4-bus Y_g - Y_g unbalanced case. (a) Voltage at bus 2. (b) Voltage at bus 4.

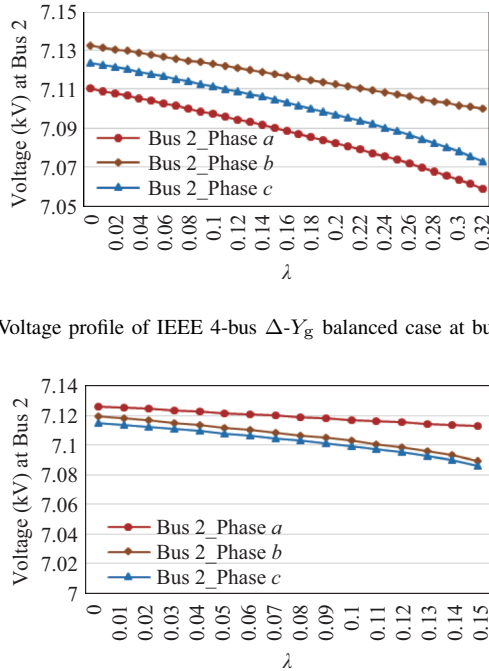


Fig. 7. Voltage profile of IEEE 4-bus Δ - Y_g balanced case at bus 2.

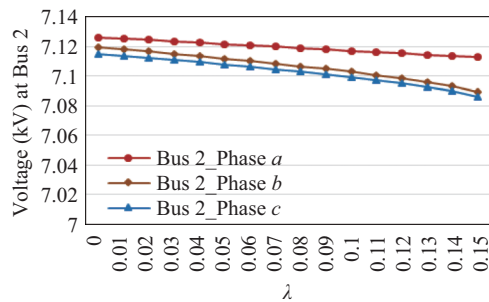


Fig. 8. Voltage profile of IEEE 4-bus Δ - Y_g unbalanced case at bus 2.

Three cases in each system configuration are considered: a) an un-optimized case, this is subjected to the condition that controls are not available or set at initial position; b) present loading optimization: the load is increased in uniform manner and controls are optimized; c) look-ahead approach: controls are optimized looking at one step ahead.

1) Balanced Distribution System

10 Bus System

A 10-bus balanced distribution system is considered for this

study. It contains 9 load points and the total system load is 12.368 MW. A single line diagram of the network is presented in Fig. 9. Three shunts of maximum capacity 0.08 p.u. are considered in the system at bus 8, 9 and 10. Table II shows the variation in controls for each case when objective functions (5, 10, 11, 13) are considered respectively.

It is clear from Table II that all the objectives are giving almost similar results but the computational efforts are minimum with the objective in (5). The performance time of each objective function is shown in Table III. The objective in (5) has a lower performance time, so the objective of (5) is used in further studies.

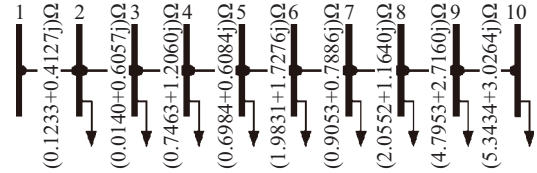


Fig. 9. Single line diagram of 10-bus balance distribution system.

TABLE II
CONTROLS FOR 10 BUS SYSTEM WITH DIFFERENT OBJECTIVE FUNCTIONS

Objective	Case	Control			Max. Loading
		Shunt (10)	Shunt (9)	Shunt (8)	
Obj_{Ploss} (5)	Un-optimized	0.000	0.000	0.000	1.060
	Present optimization	0.020	0.052	0.076	1.380
	Look-ahead approach	0.076	0.080	0.080	1.480
Obj_{Qloss} (10)	Un-optimized	0.000	0.000	0.000	1.060
	Present optimization	0.028	0.040	0.080	1.380
	Look-ahead approach	0.076	0.080	0.080	1.480
Obj_{VSI} (11)	Un-optimized	0.000	0.000	0.000	1.060
	Present optimization	0.076	0.072	0.016	1.340
	Look-ahead approach	0.076	0.080	0.080	1.480
$Obj_{(Ploss,VSI)}$ (13)	Un-optimized	0.000	0.000	0.000	1.060
	Present optimization	0.024	0.044	0.080	1.380
	Look-ahead approach	0.076	0.080	0.080	1.480

TABLE III
THE DISTRIBUTION OF THE PAPERS

Objective Function	Obj_{Ploss} (5)	Obj_{Qloss} (10)	Obj_{VSI} (11)	$Obj_{(Ploss,VSI)}$ (13)
Performance	1207.89	1227.2	2469.36	2971.72
Time (sec.)				

52 Bus System

An 11 KV, 52-bus practical distribution system [23] is also used in this study. Fig. 10 shows the schematic diagram of a 52-bus distribution system. The shunts are considered at bus 44, 50 and 52. The locations of the shunts are calculated by performing a voltage sensitivity analysis. As stated in an earlier section; the objective of (5) is used in this study. Table IV shows that the loadability of the system is enhanced using a look-ahead approach by 35.135% from the un-optimized case and by 10.811% from the present optimization case.

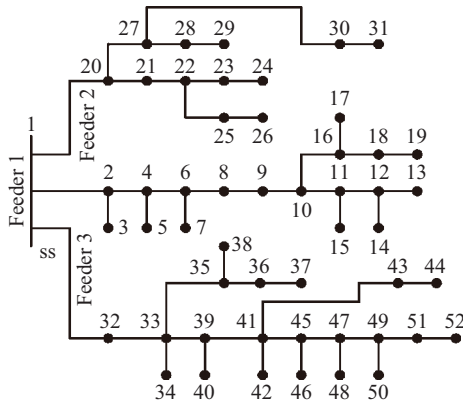


Fig. 10. Schematic diagram of a 52-bus balanced distribution system.

TABLE IV
CONTROLS FOR A 52-BUS DISTRIBUTION SYSTEM

Objective	Case	Controls			Max. Loading
		Shunt (50)	Shunt (52)	Shunt (44)	
$Obj_{P_{loss}}$	Un-optimized	0.000	0.000	0.000	0.240
	Present optimization	0.400	0.600	0.600	0.330
	Look-ahead approach	0.600	0.900	0.900	0.370

2) Unbalanced Distribution Systems with Transformer

Due to the lesser computational efforts, active power loss minimization is utilized as the objective for the IEEE 4-bus and modified 25-bus unbalanced distribution systems. The detailed mathematical model is presented in section IV-B in (14) and (20). For the IEEE 4-bus and modified 25-bus unbalanced system, a total of nine combinations of transformer connections are possible as described in [16]. In this paper, due to the limitation of space, results are shown only for four combinations taking care of all types of transformer winding connections (Y , Y_g , Δ).

The on-load-tap-changer (OLTC) transformers are used to maintain the voltage levels. In this study, voltage at the secondary winding is controlled. The tap changers positions are taken in discrete steps. The voltage limits are assumed to be $\pm 10\%$. The shunt capacitors are considered as susceptances connected in star or delta form at the nodes on the basis of the transformer connections. The prediction of the next load increase is shown as the load increasing linearly with a step size of 0.1 for the 4-bus system and 0.2 for the 25-bus system.

4-Bus System

Table V shows the variation of control parameters for all three cases with different transformer connections. For this system, the taps are tuned between 0.95 to 1.05 in discrete steps and two shunts of maximum 0.8 p.u. are considered at bus 3 and 4. The results shown in Table V depict that the maximum loadability enhancement is achieved with the look-ahead approach. The maximum loadability can further be increased by repeating steps 2 to 8 of the look-ahead approach till all the controls are exhausted.

25-Bus System

Figure 11 shows the single line diagram of the modified 25-bus test system. The modification is shown in the Appendix.

TABLE V
CONTROL VARIABLES FOR THE IEEE 4-BUS SYSTEM WITH DIFFERENT TRANSFORMER CONNECTIONS

Transf -ormer	Case	Controls			Max. Loading
		Tap	Shunt (4)	Shunt (3)	
$Y_g - Y_g$	Un-optimized	1.0000	0.000	0.000	0.130
	Present optimization	0.9500	0.400	0.800	0.411
	Look-ahead approach	0.9500	0.520	0.800	0.422
$Y - \Delta$	Un-optimized	1.0000	0.000	0.000	0.509
	Present optimization	0.9563	0.480	0.360	1.368
	Look-ahead approach	0.9500	0.52	0.400	1.490
$\Delta - Y_g$	Un-optimized	1.0000	0.000	0.000	0.155
	Present optimization	0.9500	0.480	0.800	0.469
	Look-ahead approach	0.9500	0.560	0.760	0.471
$\Delta - \Delta$	Un-optimized	1.0000	0.000	0.000	0.899
	Present optimization	0.9626	0.480	0.320	1.299
	Look-ahead approach	0.9563	0.480	0.320	1.328

One transformer is considered at the substation side in the standard 25-bus distribution system [24]. The actual test system used in this study has 26 buses and 24 branches. The base case results for the standard 25-bus system are validated with [24] and the ETAP unbalanced load flow module.

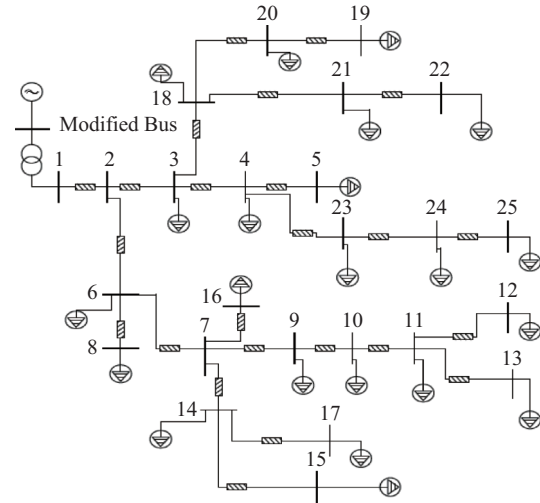


Fig. 11. Single line diagram of the 25-bus distribution system.

TABLE VI
CONTROL VARIABLES FOR THE MODIFIED 25-BUS DISTRIBUTION SYSTEM WITH DIFFERENT TRANSFORMER CONNECTIONS

Transformer Connection	Case	Controls				Maximum Loading
		Tap	Shunt (13)	Shunt (26)	Shunt (23)	
$Y_g - Y_g$	Un-optimized	1.0000	0.000	0.000	0.000	2.105
	Present optimization	0.9500	0.190	0.110	0.200	3.377
	Look-ahead approach	0.9500	0.190	0.170	0.180	3.443
$Y - \Delta$	Un-optimized	1.0000	0.000	0.000	0.000	2.299
	Present optimization	0.9500	0.150	0.060	0.010	4.362
	Look-ahead approach	0.9626	0.170	0.070	0.050	4.406
$\Delta - Y_g$	Un-optimized	1.0000	0.000	0.000	0.000	2.106
	Present optimization	0.9500	0.200	0.100	0.200	3.373
	Look-ahead approach	0.9500	0.190	0.200	0.150	3.442
$\Delta - \Delta$	Un-optimized	1.0000	0.000	0.000	0.000	2.262
	Present optimization	0.9500	0.150	0.060	0.070	4.362
	Look-ahead approach	0.9563	0.180	0.070	0.070	4.431

In the modified system, the shunts are considered at bus 13, 23 and 26. The locations of the shunts are calculated by performing a voltage sensitivity analysis. Table VI shows the variation of control parameters for the un-optimized, present loading optimization and look-ahead approach with different transformer connections. It can be observed from Table VI that maximum loading is achieved with the look ahead approach.

VI. CONCLUSION

Voltage collapse begins at the load ends under stressed conditions. Therefore, assessing and enhancing voltage stability in the distribution system is important. Since the straight forward extension of the transmission system methods may not work well for distribution systems, the new and simple voltage stability indicator have been developed in this paper. These are then used in different ways for voltage stability enhancement. Results for a few balanced and unbalanced systems confirm the potential of the proposed indicators.

Due to increased loading, voltage collapse may cause the failure of the power system. Increase in the loadability limit helps in supplying more demand without loss of voltage stability. Therefore, a look ahead approach is proposed for loadability enhancement of the distribution networks. The look ahead approach is implemented for balanced and three phase unbalanced distribution networks. Results are obtained for three standard test systems. The obtained results demonstrate the potential of the proposed approach.

APPENDIX

A. Modification in 25-Bus Data:

A transformer is incorporated between a modified bus and bus 1 in a standard 25-bus distribution system.

The leakage impedance of the transformer is $0.025 + 0.24i$. The maximum and minimum limits of the load bus voltages are $\pm 10\%$ i.e. 1.10 p.u. and 0.9 p.u..

The shunts are considered at bus 13, 23, 26 with a maximum availability of 0.2 p.u.

The minimum and maximum limit of the transformer tap is 0.95 p.u. and 1.05 p.u.

B. Parameters for Improved Harmony Search Algorithm:

HMCR = 0.98
PAR = 0.1 to 0.99
HMS = 20
T_{max} = 1000

where HMCR is harmony memory consideration rate, PAR is patch adjustment Rate, HMS is the size of harmony memory library and T_{max} is maximum number of iterations.

C. Distribution System Power Flow

1) Transformer Models and Handling

In general, a three-phase two-winding transformer is represented by two coupled coils as shown in Fig. 12.

$$\begin{bmatrix} I_p \\ I_s \end{bmatrix} = \begin{bmatrix} Y_{pp} & Y_{ps} \\ Y_{sp} & Y_{ss} \end{bmatrix} \times \begin{bmatrix} V_p \\ V_s \end{bmatrix} \quad (29)$$

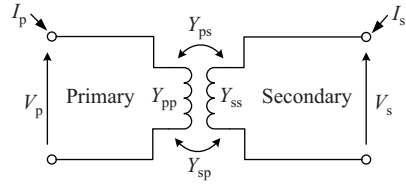


Fig. 12. Three-phase two-winding transformer.

where $\begin{bmatrix} Y_{pp} & Y_{ps} \\ Y_{sp} & Y_{ss} \end{bmatrix} = Y_T$ (admittance matrix) and Y_{pp} , Y_{ps} , Y_{sp} and Y_{ss} are the 3×3 matrix.

The value of Y_{pp} , Y_{ps} , Y_{sp} and Y_{ss} can be decided based on three sub matrices Y_1 , Y_2 and Y_3 . Table VII shows submatrices for the three phase transformer step down connection [14].

TABLE VII

Winding Connection		Self-Admittance		Mutual Admittance	
Primary	Secondary	Primary	Secondary	Primary	Secondary
Y_g	Y_g	Y_1	Y_1	$-Y_1$	$-Y_1$
Y_g	Y_g	Y_2	Y_2	$-Y_2$	$-Y_2$
Y_g	Δ	Y_1	Y_2	Y_3	Y_3^T
Y	Y_g	Y_2	Y_2	$-Y_2$	$-Y_2$
Y	Y	Y_2	Y_2	$-Y_2$	$-Y_2$
Y	Δ	Y_2	Y_2	Y_3	Y_3^T
Δ	Y_g	Y_2	Y_1	Y_3	Y_3^T
Δ	Y	Y_2	Y_2	Y_3	Y_3^T
Δ	Δ	Y_2	Y_2	$-Y_2$	$-Y_2$

where $Y_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $Y_2 = \frac{1}{3} \times \begin{bmatrix} 2y_t & -y_t & -y_t \\ -y_t & 2y_t & -y_t \\ -y_t & -y_t & 2y_t \end{bmatrix}$ and $Y_3 = \frac{1}{\sqrt{3}} \times \begin{bmatrix} -y_t & y_t & 0 \\ 0 & -y_t & y_t \\ y_t & 0 & -y_t \end{bmatrix}$ and y_t is the transformer leakage admittance in per unit.

2) Singularity Problem Handling [15]

Some reforms are needed to accommodate the distribution transformer in the backward/forward algorithm and to avoid the singularity problem of the transformer solution. In the backward and forward step, the secondary current and primary voltage can be computed as follows:

$$(I_s - Y_{ss} \cdot V_s) = Y_{sp} \cdot V_p \quad (30)$$

$$(I_p - Y_{pp} \cdot V_p) = Y_{ps} \cdot V_s \quad (31)$$

For all the connections of the transformer except the $Y_g - Y_g$ connection, the equation can be replaced as:

$$V_p = V_p^{(1+2)} + V_p^0 \quad (32)$$

$$V_p^{(1+2)} = Y_{sp}^{'-1} (I_s' - Y_{ss}' \cdot V_s) \quad (33)$$

$$V_p^0 = \frac{(V_p^a + V_p^b + V_p^c)}{3} \quad (34)$$

where, $V_p^{(1+2)}$ contains the positive and negative sequence component and V_p^0 is the zero sequence component of the voltages. Y_{ss}' and I_s' are obtained by putting zero in their last row. Y_{sp}' is obtained by replacing the last row of Y_{sp} with 1. Similar steps are followed in both the backward and forward approaches.

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