Implementation of Expert System for Power System Voltage Stability Improvement

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***Abstract*—This paper presents a concept of an expert system to monitor and improve the voltage stability condition in a power system based on the *L*-index of load busses. This index uses the load flow analysis information from the steady state voltages condition and is in the range of 0 which is indicated for no load condition to 1 which is indicated for voltage collapse. For improving the voltage stability index the control variable consists of switchable shunt VAR compensators (SVC), OLTC transformers and generator excitation. The control of voltage collapse is based on reducing the magnitude of *L*-indices of critical bus for a given system operating condition based on heuristic criteria using the sensitivities (change in *L*-index) of load busses to different reactive power control variables. These sensitivities are stored in the knowledge base of expert system in the form of facts called voltage stability control lists. The expert system identifies the critical load busses whose *L*-index values are above acceptable limits. The expert system selects the corresponding voltage stability control list and recommends control action at the most effective compensator. The proposed expert system technique has been tested on a standard test system. Results obtained for a modified IEEE-30 bus standard test system are presented for illustration purposes.**

***Index Terms*—excitation, expert systems, *L*-index, OLTC transformer, reactive power, switchable VAR compensator, voltage stability**

I. Introduction

Voltage collapse analysis involves both static and dynamic factors. From a system operators view point a stressed (heavy loaded) system has to be carefully monitored and adequate control action taken when the operating point approaches the limit of voltage stability. In a day-to-day operation and control of power systems these decisions require very fast computations in Energy Control Center [1]. Conventional optimization techniques of voltage stability improvement are computationally intensive, and hence there is a need for a heuristic approach which can give decisions very fast with a minimum of numerical computations.

II. Proposed Approach

The proposed expert system technique against voltage collapse is based on reducing the magnitude of *L*-indices of critical nodes [2]-[5] for a given system operating condition based heuristic criteria as shown in Fig. 1. The heuristic criteria consists of voltage stability control lists stored in the knowledge base of expert system. The voltage stability control list indicates in order of preference the most effective compensator for voltage stability improvement (*L*-index reduction) at given load bus. Three such facts are stored for each load bus, each for switchable shunt VAR compensators, OLTC transformers and generators excitation.

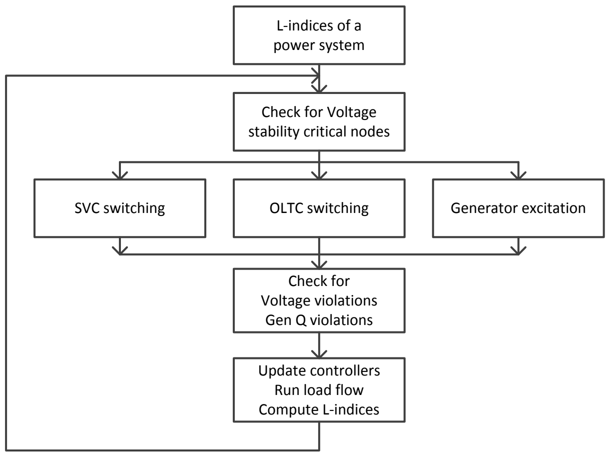

Figure 1. Proposed expert system for voltage stability improvement.

The expert system identifies the critical load busses which have *L*-index values above capable limits. The expert system selects the corresponding voltage stability control list and recommends control action at the most effective compensator. Before recommending controller switching the expert system checks for new voltage violations and generator *Q* injection violations. If due to a controller switching new violations are created then the expert system will block the switching of that controller. The voltage stability control lists, shunt compensation voltage stability control list (*SVSCL*), transformer tap voltage stability control (*TVSCL*) and generator excitation voltage stability control list (*GVSCL*) are computed for a given network configuration (base case or credible network contingency O_t) and operating condition (light load, peak load, etc.). If there is a change in the network configuration or operating (loading) conditions then the voltage stability control lists are re-computed and the knowledge base is updated. If a new contingency occurs for which the knowledge base is not available in the

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expert system, then conventional optimization technique has to be performed to update the knowledge base.

III. Knowledge Based for Voltage Stability Expert System

The knowledge base of the proposed expert system consist of (i) Voltage stability sensitivities (change in L-index) of load busses to different reactive power controllers, (ii) Voltage sensitivities (change in voltage magnitude) of load busses to different reactive power controllers, and (iii) Generator Q injection sensitivities to different reactive power controllers [6]-[7]. The procedure for computing and using voltage sensitivities are defined as follows: *SCVIL*, shunt compensation voltage improvement lists; *TCVIL*, transformer compensation voltage improvement lists; and *GCVIL*, generator excitation voltage improvement lists; and generation Q injection sensitivities are *QCSSL*, generator Q shunt sensitivity list; *GQTSL*, generator Q transformer sensitivity list; *GQGSL*, generator Q generator sensitivity list.

The voltage stability sensitivities consist of 3 facts for each load bus, viz.

Shunt compensation voltage stability control, $SVSCL(O_t, N_i, [C_p, C_q, \ldots,])$.

Transformer tap voltage stability control, $TVSCL$ $(O_t, N_i, [T_p, T_q, \ldots,], [T_l, T_k, \ldots,])$.

Generator excitation voltage stability control, $GVSCL(O_t, N_i, [G_p, G_q, \ldots,])$.

The *SVSCL* indicates that for network contingency O_t, (t: contingency, t = 0 indicates base network), for node N_i the most effective shunt compensator for voltage stability improvement is C_p, the next most effective shunt compensator for voltage stability improvement is $C_q$and so on.

The *TVSCL* indicates that for network contingency O_t (t: contingency, t = 0 indicates base network), for node N_i the most effective OLTC transformer for voltage stability improvement with tap increase is T_p, the next most effective OLTC transformer is T_q and so on. While for a tap decrease the most effective OLTC transformer for voltage stability improvement is T_l, the next most effective OLTC transformer T_k and so on. Whenever a change occurs in the operating (loading) conditions for a given network configuration, there are possibilities of a change in the sensitivity of OLTC transformers. The sensitivities of OLTC transformers to L-indices of load busses are computed and *TVSCL* is updated. The *GVSCL* indicates that for network contingency O_t (t: contingency, t = 0 indicates base network), for node N_i the most effective generator for voltage stability improvement is G_p, the next most effective generator for voltage stability improvement is G_q and so on. These facts are obtained by computing the sensitivities of load busses to change in the L-index for different reactive power control variables as explained in [5]. For a system with n nodes and g number of generators, there are (n-g) number of *SVSCL*, *TVSCL* and *GVSCL* facts for each contingency. For the modified IEEE-30 Bus system there are six generators. This system has 30-6 = 24 *SVSCL*, *TVSCL* and *GVSCL* facts stored in the knowledge base for each network contingency.

IV. L-Index Sensitivity Computation

The L-index for node j can be written as,

$$L_j^2 = \left[1.0 - \sum_{k=1}^{k=g} \frac{V_k}{V_j} F_{jk}^r\right]^2 + \left[\sum_{k=1}^{k=g} \frac{V_k}{V_j} F_{jk}^m\right]^2 \tag{1}$$

The relation between the L-index of a load bus and the reactive power control variables can be expressed as,

$$\frac{\partial L_j^2}{\partial X} = \frac{\partial L_j^2}{\partial V}\frac{\partial V}{\partial X} \tag{2}$$

where $j = g+1,\ldots, n$ and $X = [\Delta T_1, \Delta T_2, \ldots, \Delta T_t, \Delta V_1, \Delta V_2, \ldots, \Delta V_g, \Delta Q_1, \Delta Q_2, \ldots, \Delta Q_s]$ and $V = [\Delta V_1, \Delta V_2, \ldots, \Delta V_n]$.

The first term on the RHS of (2) is,

$$\frac{\partial L^2}{\partial V} = \begin{bmatrix} \frac{\partial L_{g+1}^2}{\partial V_1} & \cdots & \frac{\partial L_{g+1}^2}{\partial V_n} \\ & \vdots & \\ \frac{\partial L_j^2}{\partial V_1} & \cdots & \frac{\partial L_j^2}{\partial V_n} \\ & \vdots & \\ \frac{\partial L_n^2}{\partial V_1} & \cdots & \frac{\partial L_n^2}{\partial V_n} \end{bmatrix} \tag{3}$$

The term of the RHS of (3) ($\frac{\partial L_j^2}{\partial V_i}$ where $j = g+1, ..., n$ and $i = 1, .. g, g+1,.., n$) can be evaluated as follows,

The denominator voltage is a generator voltage ($\frac{\partial L_j^2}{\partial V_i}$, here $i = g, g+1$) then

$$\frac{\partial L_j^2}{\partial V_i} = 2\left[1.0 - \sum_{k=1}^{k=g} \frac{V_k}{V_j} F_{jk}^r\right]\left[-\frac{F_{ji}^r}{V_j}\right] + 2\left[\sum_{k=1}^{k=g} \frac{V_k}{V_j} F_{jk}^m\right]\left[\frac{F_{ji}^m}{V_j}\right] \tag{4}$$

the denominator voltage is a load voltage and $i = j$ ($\frac{\partial L_j^2}{\partial V_i}$, here $i = g+1, \ldots, g$ and $i = j$) then,

$$\frac{\partial L_j^2}{\partial V_j} = 2\left[1.0 - \sum_{k=1}^{k=g} \frac{V_k}{V_j{}^2} F_{jk}^r\right]\left[-\frac{F_{ji}^r}{V_j}\right] + 2\left[\sum_{k=1}^{k=g} \frac{V_k}{V_j} F_{jk}^m\right]\left[-\sum_{k=1}^{k=g} \frac{V_k}{V_j{}^2} F_{jk}^m\right] \tag{5}$$

else if the denominator voltage as a load voltage and $i \neq j$ ($\frac{\partial L_j^2}{\partial V_i}$, here $i = g+1, \ldots, n$ and $i \neq j$) then

$$\frac{\partial L_j^2}{\partial V_1} = 0 \tag{6}$$

Equation (3) can be written as,

$$\frac{\partial L^2}{\partial V} = \begin{bmatrix} S_G & S_L \end{bmatrix} \tag{7}$$

where,

$S_G = \frac{\partial L_j^2}{\partial V_i}$, j = g+1, …,n and i = 1, …, g and has dimension of (n-g) x (g)

$S_L = \frac{\partial L_j^2}{\partial V_i}$, j = g+1, …,n and i = 1, …, n and has dimension of (n-g) x (n-g)

Substituting (7) in (2) we obtain,

$$\frac{\partial L^2}{\partial X} = \begin{bmatrix} S_G & S_L \end{bmatrix} \frac{\partial V}{\partial X} \tag{8}$$

Substituting for the load voltages, ΔV_L in terms of the reactive power control variables and (8) can be written as,

$$\frac{\partial L^2}{\partial X} = [S_G][\Delta V_G] + [S_L][H] \begin{bmatrix} \Delta T_T \\ \Delta V_G \\ \Delta Q_s \end{bmatrix} \tag{9}$$

$$\frac{\partial L^2}{\partial X} = \left[S^{'}\right] \begin{bmatrix} \Delta T_T \\ \Delta V_G \\ \Delta Q_s \end{bmatrix} \tag{10}$$

V. Expert System Rules

The voltage profile is assumed to be available from the output of the on-line state estimator (which for simulation purpose is obtained from an operational load flow) and $\overline{F}^{GL}$ values are computed for a given network configuration using data from the network data bank. The L-indices for the load busses are computed using (1). The L-indices thus computed, the present, minimum and maximum settings of different controllers form the input to the expert system. The expert system monitors the L-index values and if it exceed acceptable limits (based on utility policy and practice) then the expert system flags that the particular bus as critical for voltage stability improvement. The expert system arranges the critical busses in the form of a list, called voltage stability critical list, *VSCL* (N_i, N_j,…) where node N_i has the largest L-index value, node N_j the next largest L-index value and so on. The expert system initializes three switching list to zero, viz,

- Shunt compensation switching list, *SSL* (ΔC_1, ΔC_2, …, ΔC_s).
- Transformer tap switching list, *TSL* (ΔT_1, ΔT_2, …, ΔT_s).
- Generator excitation switching, *GSL* (ΔV_1, ΔV_2, …, ΔV_s).

The expert system picks a node from the top of *VSCL* and its corresponding *SVSCL*, *TVSCL* and *GVSCL* facts. The expert system selects the two most effective compensators from each list for one step switching. In case of OLTC transformers if the expert system recommends tap change in both directions (increase and decrease) for different node in the *VSCL*, then the tap change for that OLTC transformer is blocked. The expert system checks if the recommended switching action lead to any new voltage violations using *SCVIL*, *TCVIL* and *GCVIL* facts and generator Q injection violations using *GQSSL*, *GQTSL* and *GQGSL* facts. If now our violations are detected then the expert system recommends one step change by updating the corresponding switching lists. This process is repeated for all the nodes in *VSCL* such that for a selected compensator only one step change is recommended. A load flow result is obtained with the updated values of control variables as indicated by the controller switching list and the whole process is repeated till all nodes have L-index within acceptable limits or no further scope exists for switching controllers. The expert system is implemented in the form IF-THEN rules as follows:

Rule-1 Form the input data available (state estimation) check for the network configuration O_t, (t = 0.1,…,t = 0 indicates base case normal network condition).

Rule-2 Scan the L-indices of all the load busses and if they are within acceptable limits then exit with success else form the following lists:

- Voltage stability critical list, *VSCL* (N_i, N_j, …) where N_i is the node with the largest L-index value, N_j the node with the next largest L-index value and so on.
- Shunt compensation switching list, *SSL* (ΔC_1, ΔC_2, …,ΔC_s) initialized to zero.
- Transformer tap switching list, *TSL* (ΔT_1, ΔT_2, …,ΔT_s) initialized to zero.
- Generator excitation switching, *GSL* (ΔV_1, ΔV_2, …,ΔV_s) initialized to zero.

Rule-3 Pick a node from the top of *VSCL*, (N_c), and its corresponding *SVSCL*, *TVSCL* and *GVSCL* facts:

- *SVSCL* (O_t, N_c, [C_p, C_q, …]).
- *TVSCL* (O_t, N_c, [T_p, T_q, …], [T_l, T_k,…]).
- *GVSCL* (O_t, N_c, [G_p, G_q, …]).
- Select two most effective compensators from each voltage stability control list (*SVSCL*, *TVSCL* and *GVSCL* facts are arranged in order of priority) for voltage stability improvement.

Rule-4 For the selected controllers check if margin is available for one step controller switching,

- $C_i^0 < C_i^{\max}$ for SVC switching.
- $T_i^0 < T_j^{\max}$ for OLTC tap increase.
- $T_i^0 < T_i^{\min}$ for OLTC tap decrease.
- $V_i^0 < V_i^{\max}$ for generator excitation increase.
- If margin for switching is available at all the selected controllers then go to rule-6.

Rule-5 If margin for switching at a particular controller (say SVC) is not available then choose the next most effective compensator from the corresponding voltage stability control list (example *SVSCL*) and go to rule-4.

Rule-6 For the controller switching selected in rule-4, compute the new system voltage profile:

- $V_j^{new} = V_j^0 + S_{cp}^j$ for SVC C_p switching, where j = g+1,…, n and S_{cp}^j is the voltage sensitivity of node

j to shunt compensator C_p and is available from the *SCVIL* fact *SCVIL* (O_t, N_c, [C_p, C_q, …], [$S_{cp}^j, S_{cq}^j, \ldots$]).

- $V_j^{new} = V_j^0 + S_{tp}^j$ for OLTC transformer T_p switching, where j = g+1,…, n and d_i indicates direction of tap change (+1 for increase and –1 for decrease) and S_{tp}^j is the voltage sensitivity of node j to OLTC transformer T_p and is available from the *TCVIL* fact *SCVIL* (O_t, N_j, [T_p, T_q, …], [$S_{tp}^j, S_{tq}^j, \ldots$]).
- $V_j^{new} = V_j^0 + S_{gp}^j$ for generator G_p switching, where j = g+1,…, n and S_{gp}^j is the voltage sensitivity of node j to generator excitation change at G_p and is available from the *GCVIL* fact *GCVIL* (O_t, N_j, [G_p, G_q, …], [$S_{gp}^j, S_{gq}^j, \ldots$]).

Rule-7 Check if any new voltage violations are created

$$(V_j^{\min} \le V_j^{new} \le V_j^{\max}).$$

- $V_j^{new} > V_j^{\max}$ for capacitive SVC switching.
- $V_j^{new} < V_j^{\min}$ for inductive SVC switching.
- $V_j^{\min} < V_j^{new} < V_j^{\max}$ for OLTC switching.
- $V_j^{new} > V_j^{\max}$ for excitation increase.
- $V_j^{new} < V_j^{\min}$ for excitation decrease.
- In case new voltage violations occur due to a particular controller switching (say generator excitation) then switching is blocked for that particular controller (corresponding term in the switching list (example *GSL*) will not be updated) and the next most effective controller is picked from the corresponding voltage stability control list (example *GVSCL*. Go to rule-4.

Rule-8 For the controller switching selected, compute the modified generator Q injection.

- $Q_j^{new} = Q_j^o + Q_{(cg)j}^p$ for SVC switching, where j = 1, …, g and $Q_{(cg)j}^p$ is the change in Q injection at generator j for one step shunt compensator switching at C_p and is available from *GQSSL* fact *GQSSL*

$$(O_t, C_p, [Q_{(cg)1}^p, Q_{(cg)2}^p, \ldots, Q_{(cg)g}^p]).$$

- $Q_j^{new} = Q_j^o + Q_{(tg)j}^p d_i$ for OLTC transformer T_p switching, where j = 1, …, g and d_i indicates direction of OLTC transformer tap change and $Q_{(tg)j}^p$ is the change in Q injection at generator j for one step tap change at OLTC transformer T_p and is available from *GQTSL* fact *GQTSL* $(O_t, T_p, [Q_{(tg)1}^p, Q_{(tg)2}^p, \ldots, Q_{(tg)g}^p])$.
- $Q_j^{new} = Q_j^o + Q_{(gg)j}^p$ for generator excitation change at V_p, where j = 1, …, g and $Q_{(gg)j}^p$ is the change in Q injection at generator j for one step excitation change generator p and is available from *GQGSL* fact *GQGSL*

$$(O_t, G_p, [Q_{(gg)1}^p, Q_{(gg)2}^p, \ldots, Q_{(gg)g}^p]).$$

Rule-9 For each controller switching check if any generator Q injection violations are created $(Q_j^{\min} \le Q_j^{new} \le Q_j^{\max})$. In case generator Q injection violations occur due to particular controller switching (say OLTC) then switching is blocked for that particular controller (corresponding term in the switching list (example *TSL*) will not be updated and the next most effective controller is picked from the corresponding voltage stability control list (example *TVSCL*). Go to rule-4.

Rule-10 Update the switching lists such that for a controller only one step switching recommended,

- $\Delta C_i^{new} = \Delta C_i^o + \Delta C_i$ for SSL.
- $\Delta T_i^{new} = \Delta T_i^o + \Delta T_i$ for OLTC transformer tap increase in *TSL*.
- $\Delta T_i^{new} = \Delta T_i^o - \Delta T_i$ for OLTC transformer tap decrease in *TSL*.
- $\Delta V_i^{new} = \Delta V_i^o + \Delta V_i$ for *GSL*.
- If tap change is recommended in both directions at a particular OLTC, the switching gets blocked (all switching lists including *TSL* are initialized to zero one step increase and decrease in tap will mean no tap change at the particular OLTC).

Rule-11 If all the nodes in *VSCL* list are not processed then go to rule-3.

Rule-12 A load flow (OLF) is obtained with the updated reactive power controller values as indicated by the switching list and the *L*-indices are computed for all the load busses. Go to rule-2.

VI. Case Study

The proposed expert system technique has been tested on a credible network of a modified IEEE-30 bus standard test system is presented. Single line diagram and data profile of the system was adopted from the [5]. The controller setting and system parameter obtained for modified IEEE-30 bus standard test system under heavy load (175% of peak load) conditions for both the proposed expert system technique and optimization technique are given in Table I.

The voltage profile and *L*-indices obtained by these two techniques are given in Fig. 2. The maximum *L*-index decrease from 0.408 initially to 0.258 in case of optimization technique and to 0.259 in case of expert system technique. The overall system index (ΣL^2) decrease from 1.084 initially to 0.503 in case of optimization technique and to 0.510 in case of expert system technique.

The minimum voltage increases from an initial value of 0.787 per unit to 0.983 per unit in case of optimization technique and to 0.982 per unit in case of expert system technique and all at node 30. The system losses also decrease from an initial value of 24.05 MW initially to 20.19 MW in case of optimization technique and to 20.29 MW in case of expert system technique.

TABLE I. CONTROLLER SETTINGS OF MODIFIED IEEE-30 BUS STANDARD TEST SYSTEM

Controller	Modified IEEE-30 Bus Standard Test System		
	Initial	Optimization Technique	Expert System Technique
T1	1.0	0.9	0.9
T2	1.0	0.9	0.9
T3	1.0	0.9	0.9
T4	1.0	0.9	0.9
V1	1.0	1.05	1.048
V2	1.0	1.05	1.05
V3	1.0	1.042	1.05
V4	1.0	1.046	1.05
V5	1.0	1.05	1.05
V6	1.0	1.05	1.05
S13	0.0	10	8
S14	0.0	3	3
S15	0.0	5	5
S16	0.0	10	10
S18	0.0	7	7
S20	0.0	5	5
S25	0.0	5	5
S27	0.0	2	2
S30	0.0	3	5
L_{max}	L_{30} = 0.408	L_{30} = 0.258	L_{30} = 0.259
ΣL^2	V_{30} = 0.778	0.503	0.510
Vmin	20.19	V_{30} = 0.983	V_{30} = 0.982
P_{loss} (MW)	0.458	20.19	20.29
MSV		0.605	0.598

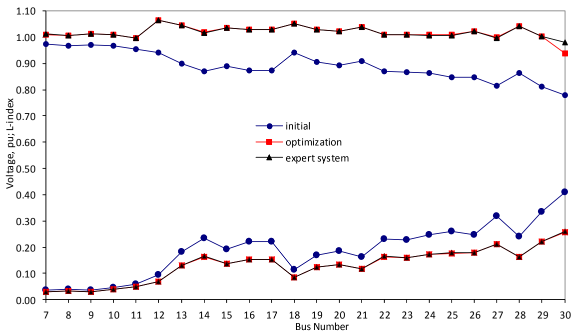

Figure 2. Voltage and *L*-index profile of modified IEEE-30 Bus system.

The minimum singular value of the modified power flow Jacobian matrix improves from an initial value of 0.458 to 0.605 in case of optimization technique and 0.598 in case of expert system technique, thus indicating an improvement in the system voltage stability margin by both techniques.

VII. CONCLUSIONS

A concept of an expert system for alleviation of network voltage is developed. The expert system solution methodology mainly depends on the voltage sensitivities of load busses and Q injection sensitivities to different reactive power controllers like switchable shunt VAR compensators, OLTC transformers and generators excitation. The performance of the expert system is compared with the proposed non-linear optimization technique for voltage improvement, and also curtailed number and reduced controller movement algorithm for voltage control. The expert system is demonstrated to alleviate the voltage violations using minimum number of controllers. The expert system gives acceptable results in real time with significant speedup.

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