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Stability Analysis of a Line Voltage using FACTS Devices

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Abstract: The analysis of voltage stability in power system networks is outlined in this document. The Fast Voltage Stability Index (FVSI) is employed to evaluate the condition of the power lines under both normal and critical load situations. It aids in identifying the vulnerable buses that require reactive power compensation. Reactive power compensation is achieved by utilizing a series of interconnected FACTS devices, which effectively improve the stability limit and mitigate the risk of voltage collapse in strained transmission lines. The paper showcases the effective utilization of FVSI in assessing the stability of transmission line voltages. Discussion has also taken place regarding the enhancement of bus voltage stability, improved line flows, and reduction of losses through the application of series FACTS compensation. The examinations were conducted on IEEE30, IEEE 57, and IEEE118 bus networks.

Keywords:
Voltage stability; Reactive power compensation; FVSI; FACTS .

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1. Introduction

The rapid growth of industries and urban areas worldwide has resulted in a significant reliance on electricity and a continuous rise in power requirements. The lack of power supply has resulted in the expansion of current networks and the creation of new ones. Power engineers and researchers often encounter the challenge of dealing with the intricate operation and structure of such networks. Due to the rising demand for power system utilities globally, the transmission lines experience significant strain, resulting in low voltage or voltage collapse.

Voltage stability refers to the ability of a power system to maintain voltages within acceptable limits at all buses under normal circumstances and when exposed to a disturbance [1]. Voltage instability leads to voltage collapse, which signifies a decline in voltage to an undesirable and inadequate level [2].

Voltage collapse is a prevalent occurrence in power systems that are typically burdened with heavy loads, faults, and/or reactive power deficiencies [4]. Voltage stability analysis is crucial to prevent power system blackouts caused by certain conditions, highlighting the significance of maintaining a secure power system with continuous power transfer.

The sole method to avert voltage collapse in the network is by either reducing the reactive power load or incorporating reactive power compensating devices to the strained lines. The incorporation of reactive power sources such as shunt capacitors and/or Flexible AC Transmission System (FACTS) controllers at specific and suitable points can lead to the desired outcome. The introduction of FACTS devices enhances the power transfer capability and minimizes line losses.

2. Voltage Stability Indices

Several methods have been used for static voltage stability analysis of power system networks. Identification of a weak bus or line is of utmost importance from the point of view of reactive power compensation. The condition of voltage stability of a power system can be ascertained by using voltage stability indices. Voltage stability indices are scalar magnitudes that help to quantify the distance of the particular operating point with the point of collapse [9]. Jacobian matrix based voltage stability indices require high computational time and so are not appropriate for online assessment. System variables based voltage stability indices use elements of the admittance matrix and other system variables like bus voltages or power flow through the lines. Computation time required is less and so these indices are useful online voltage stability assessment and monitoring [9].

2.1 Line stability Index

The power system network is designed with a greater number of lines compared to the number of buses. This is done to guarantee efficient power delivery to the utilities and enhance the overall stability of the system. As a result of the continuously rising power requirements globally, transmission lines are often heavily burdened or strained, resulting in frequent blackouts or, in some cases, complete system failure. Therefore, it is crucial to identify the vulnerable aspects of the network and implement necessary actions to prevent such occurrences. Multiple line voltage stability indices are utilized to identify stressed lines. 1. Several indices include Lmn index, LQP index, FVSI index, VCPI (Losses) index, VCPI (Power) Index, and more [6, 8, 9, 10].

2.2 FVSI Formulation

I. Musirin et al [9] proposed the Fast Voltage Stability Index (FVSI) as the Line Stability Index. The theory revolves around the transmission of power through a solitary line, stemming from the quadratic equation of voltage at the receiving end of a two-bus configuration [6, 7, 9, 11].

The stability index in a connected transmission line is determined through the following equation:

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \quad (1)$$

The line with a FVSI value nearing 1 is nearing its point of instability. If the load continues to increase, there is a possibility that either of the buses connecting the line will experience voltage collapse. When FVSI is greater than 1, it indicates that the line is facing voltage instability. The FVSI assists in pinpointing the least robust buses and the most congested lines. Consequently, understanding the FVSI also aids in the accurate positioning of reactive power compensation within the power system grid.

3. Reactive Power Compensation with FACTS devices:

Reactive power deficit in a power system network is the prime cause for voltage instability. Introduction of FACTS controllers as sources of reactive power at appropriate locations helps improve the voltage stability of the system [12]. FACTS devices are utilized to enhance the overall performance of the power system network. FACTs devices play a crucial role in enhancing the voltage profile, offering system operation flexibility, and controlling power flows, all while maintaining the system's reliability and security [13]. Typically, the controllers are best placed at the weakest bus or line for optimal positioning. Shunt FACTS controllers are utilized on the least robust bus, while series FACTS devices are employed on the line experiencing the highest level of stress [3].

In this paper, Series FACTS devices namely, TCSC (Thyristor controlled series capacitor), SSSC (Static Synchronous Series Compensator) and UPFC (Unified Power Flow Controller), are applied to the lines identified to be heavily stressed and those having FVSI value greater than 1. Of these FACTS devices used, UPFC is a combined series-shunt controller.

4. Case Study and Simulation Results

Load flow analysis and Continuation Power Flow Analysis [14] were conducted on the IEEE 30 bus, IEEE 57 bus, and IEEE 118 bus test systems. The identification of the most stressed lines approaching or experiencing voltage collapse is done by calculating the FVSI of each line. FACTS devices are then applied to these lines. The voltage magnitudes at the respective buses have been recorded. FVSI, power flows, and line losses for these connections have been computed.

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4.1 IEEE 30 bus, 41 line system

NR load flow analysis is done on the system and FVSI of each line is calculated. Continuation Power Flow (CPF) analysis is the done to find out the most stressed lines under critical loading conditions. FVSI for each line is then calculated. The weak line, having the highest value of FVSI (line 37) is then identified for reactive power compensation. TCSC, UPFC and SSSC are applied to these weak lines [Table 1].

Table 1: Highest FVSI values (IEEE 30 bus system)

Line No.	Connected buses		FVSI value				
	From bus	To bus	Base loading	Critical loading	with TCSC in line 37	with UPFC in line 37	with SSSC in line 37
37	27	29	0.26746561	2.33358423	0.04576616	0.07367929	0.002612659
36	28	27	0.03936276	0.90817999	0.040453541	0.04305532	0.041264342
12	6	10	0.21078006	0.84404272	0.210814082	0.21138803	0.210986062
4	3	4	0.18234222	0.77574773	0.182356357	0.18236313	0.182358847

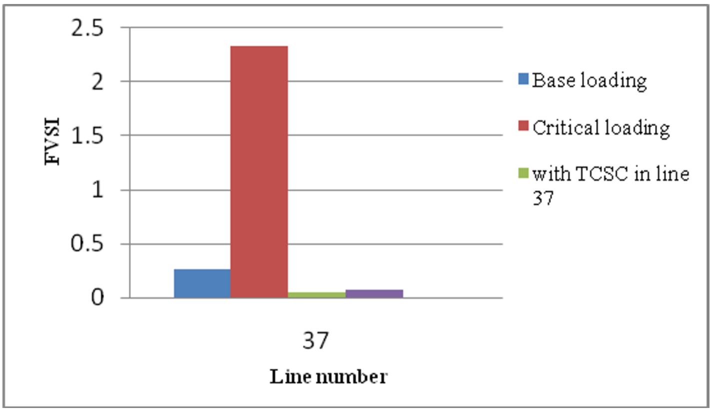

Fig 1: FVSI of the weakest line under different conditions (IEEE 30 bus system)

Table 2: Voltage magnitudes (IEEE 30 bus system)

Line no.	Connected buses	Voltage (pu)			
		No compensation	with TCSC in line 37	with UPFC in line 37	with SSSC in line 37
37	Bus 27	1.011250889	1.0120713	1.011506	1.0116828
	Bus 29	0.991150405	1.0118925	1.0044413	1.0071161

It is observed that under critical loading conditions line 37 becomes unstable (FVSI>1). FVSI value reduces from 0.2675 (base case) with application of FACTS devices, indicating that the system is secure [Fig. 1]. The voltage magnitudes of the connected buses (bus 27 and Bus 29) improve with FACTS controllers in line [Table2].

Table 3: Power flows (IEEE 30 bus system)

Line Flows (p.u)		
Line 37	P Flow	Q Flow
No comp	0.061931726	0.0167502
TCSC	0.084841813	0.0218165
UPFC	0.068040453	0.0252434
SSSC	0.079787178	0.0232206

Table 4: Line losses (line 37, IEEE 30 bus system)

Line Losses (p.u)		
Line 37	P loss	Q loss
No comp	0.000884701	0.0016716
TCSC	1.38778E-17	6.223E-05
UPFC	0	0.0014965
SSSC	0	0.0011197

Increased Real and Reactive Power flows are observed [Table 3] and Line losses reduced with FACTS compensation in line 37.

4.2 IEEE *57 bus, 80 line test system*

The same process is applied to IEEE 57 bus test system, yielding similar results. Lines 35, 36 and 76 are found to have the highest values of FVSI [Table 5], indicating that these lines are reactive power deficit. Under critical loading conditions, lines 35 and 36 becomes unstable (FVSI>1), while line 76 almost reaches instability. With application of FACTS devices the FVSI values reduce [Fig. 2] and voltage magnitudes of the connected buses increase [Table 6].

Table 5: Highest FVSI values (IEEE 57 bus system)

Line No.	Connected buses		FVSI value				
	From bus	To bus	Base loading	Critical loading	with TCSC in lines 35,36,76	with UPFC in lines 35,36,76	with SSSC in lines 35,36,76
35	24	25	0.3349093	3.6293314	0.1224418	0.1025978	0.0575877
36	24	25	0.3485096	3.7767154	0.127414	0.1067642	0.0599263
76	39	57	0.416292	0.9789888	0.3470118	0.3017123	0.1978365

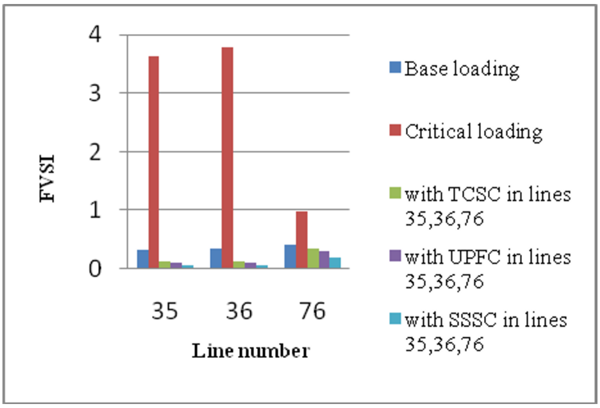

Fig 2: FVSI of the weakest lines under different conditions (IEEE 57 bus system)

Table 6: Voltage magnitudes (IEEE 57 bus system)

Line no.	Connected buses	Voltage (pu)			
		Without compensation	with TCSC in lines 35, 36, 76	with UPFC in lines 35, 36, 76	with SSSC in lines 35, 36, 76
35	Bus 24	0.999233	0.9997401	0.999	0.9998286
	Bus 25	0.9825208	0.9936824	0.993929776	0.9969784
36	Bus 24	0.999233	0.9997401	0.999	0.9998286
	Bus 25	0.9825208	0.9936824	0.993929776	0.9969784
76	Bus 39	0.9828231	0.9839188	0.983	0.9834056
	Bus 57	0.964826	0.968945	0.970018814	0.9749269

Line flows and line losses of lines 35, 36 and 76 are given in Table 7 and Table 8.

Table 7: Power flows (IEEE 57 bus system)

Line no.	Line Flows (p.u) P Flow Without compensation	with TCSC	with UPFC	with SSSC	Q Flow Without compensation	with TCSC	with UPFC	with SSSC
35	0.070674252	0.07751	0.078396	0.0806	0.017140366	0.01273	0.01218	0.01061
36	0.067916232	0.07448	0.075336	0.07745	0.016471473	0.01223	0.0117	0.01019
76	0.038526387	0.0569	0.060661	0.07174	0.029205566	0.02457	0.02459	0.02552

Table 8: Line losses (IEEE 57 bus system)

Line No.	Line Losses (p.u) P loss Without compensation	with TCSC	with UPFC	with SSSC	Q loss Without compensation	with TCSC	with UPFC	with SSSC
35	0	0	0	0	0.006260775	0.00337	0.00298	0.00195
36	0	0	0	1.4E-17	0.006016452	0.00324	0.00287	0.00188
76	2.08167E-17	-6.939E-18	0	0	0.003148803	0.00249	0.0024	0.00203

4.3 Modified IEEE 118 bus, 186 line test system

Similar tests are carried out on the modified IEEE 118 bus system and lines 62, 68 and 175 are found to be the most stressed lines [Table 9]. Line 62 is unstable under base load condition (FVSI>1), while lines 68 and 175 becomes unstable under critical loading conditions. Application of FACTS devices yield favorable results [Fig. 3]. FVSI values of the lines under test are reduced Voltage magnitudes, Line flows and Line losses are then computed [Tables 10, 11 and 12]. Line flows are substantially enhanced with the use of UPFC, indicating that shunt FACTS compensation would yield better results in this system.

Table 9: Highest FVSI values (modified IEEE 118 bus system)

Line No.	Connected buses From bus	To bus	FVSI value Base loading	Critical loading	with TCSC in lines 62, 68, 175	with UPFC in lines 62, 68, 175	with SSSC in lines 62, 68, 175
62	45	46	1.16981	5.1021195	0.7158272	0.9160975	0.6616325
68	45	49	0.8315856	3.0288288	0.5781852	0.6818247	0.5481737
175	109	110	0.7735789	3.1998538	0.7595491	0.8493312	0.7581995

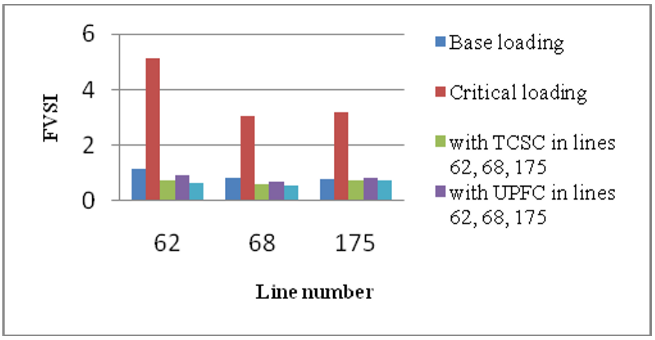

Fig 3: FVSI of the weakest lines under different conditions (modified IEEE 118 bus system)

Table 10: Voltage magnitudes (modified IEEE 118 bus system)

Line no.	Connected buses	Voltage (pu)			
		Without compensation	with TCSC in lines 62, 68, 175	with UPFC in lines 62, 68, 175	with SSSC in lines 62, 68, 175
62	Bus 45	0.97632	1.0067729	0.987	1.0108336
	Bus 46	1.005	1.005	1.005	1.005
68	Bus 45	0.97632	1.0067729	0.987	1.0108336
	Bus 49	1.025	1.025	1.025	1.025
175	Bus 109	0.967156	0.9725387	0.967	0.9725387
	Bus 110	0.973	0.973	0.973	0.973

Table 11: Power flows (modified IEEE 118 bus system)

Line no.	Line Flows (p.u)							
	P Flow				Q Flow			
	Without compensation	with TCSC	with UPFC	with SSSC	Without compensation	with TCSC	with UPFC	with SSSC
62	-0.01517149	0.21799	0.754	0.293565	-0.217710909	0.066452	-0.1599	-0.05388
68	-0.30021892	-0.5714	0.701	-0.64247	-0.160519529	-0.48741	-0.2564	-0.37753
175	-0.24233411	-0.2895	0.53	-0.28951	0.007289128	-0.02877	-0.1008	-0.02877

Table12: Line losses (modified IEEE 118 bus system)

	Line Losses (p.u)							
Line No.	P loss				Q loss			
	Without compensation	with TCSC	with UPFC	with SSSC	Without compensation	with TCSC	with UPFC	with SSSC
62	0.00172005	0	0	0.003427	-0.026758553	0.00139	0.05785	-0.0221102
68	0.00786128	0	0	1.11E-16	-0.023107749	0.020703	0.07449	0.0202166
175	0.00175367	0	0	-5.6E-17	-0.014202594	0.001364	0.01657	0.0013638

5. Conclusion

In this paper FVSI is used to determine the voltage stability of different test systems and the weak lines are identified. Application of series FACTS controllers to the weak lines has helped in improving the FVSI values of the lines under test, indicating that voltage stability of these lines have been achieved. Changes are also observed in voltage magnitudes, line flows and line losses in the process. FVSI is therefore found to be a very efficient index for weak line identification and voltage stability assessment due to simplicity in computation and faster response.

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