



ESTIMATING THE COLLAPSE POINT OF A TRANSMISSION LINE IN A DEVELOPING POWER SYSTEMS

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ABSTRACT

The trouble with a developing national grid is compounded by the fact that the power system supplies power to a vast number of loads which is fed by a number of generating units sometimes far from the load centers. Variations of loads bring about power losses and corresponding increase in the reactive power requirements of the transmission systems. Thus, the paper is aimed at establishing the point of collapse of transmission lines to enable a control system operator to take proactive measures in the event of small/large system disturbances. Voltage collapse proximity indicator is exploited to show that the variations in load close to the maximum load require extremely large amounts of reactive power at the sending end in order to support the increase in load. In the work, it was identified that Katemkpe-Shiroro transmission line is the most critical transmission line contributing immensely for voltage collapse scenarios in Nigeria national grid. Consequently, it ranked first because it has the highest voltage collapse proximity index. Computation involving voltage collapse proximity indicator obtained the collapse point or the knee point as 2.8684. This serves as a criterion that will enable control system expert to take proactive measure before the impending voltage collapse

1.0 Introduction

Nigerian national grid (NNG) is a network of electricity transmission lines connecting generating buses to load buses across the entire country (Mbah, 2022). The network is designed to operate within certain stability limits. The statutory limit for voltage is 0.95 to 1.05 per unit and that of frequency is 50Hz+5 per cent. Whenever the grid operates out of these stability ranges there would be a sequence of events accompanying voltage instabilities that bring about voltage collapse. These usually occur whenever transmission lines are stressed beyond their fold or knee point. There is an urgent need to determine the point of collapse of some of the components of the power supply system like the transmission line to enable the power control expert to take proactive measures before the saddle node bifurcation point of the entire system is reached. For the past 36 years, there are a total of 750 scenarios (Onah et al., 2018; 2019; 2021,). From the return of democratic rule in Nigeria, the country has had worrisome challenges in the power industry. Between 1999 and 2014, there were 478 incidents of voltage collapse. The worst case took place between 2003 and 2004 with an average of 52 incidents. From 2015 to date the Figure is estimated to be 98 incidences (Samuel et al., 2014).

Uncertainty has trailed the causes of incessant voltage collapse incidences in Nigeria national grid (NNG). The information relating to the cause of national blackout from September 2021 to June 2022 kept energy users and the utility companies in the dark (TCN, 2022). For close to four decades, Nigeria national grid encountered an average of 22 incidences of voltage

collapse per year in the year 2018. It is observed that the Figure declined to an average of 20.83 in the year 2022 (Samuel et al., 2014). Recently, Mbah (2022) reported that the Nigerian national grid encountered seven incidences of partial and total voltage collapse in the year 2022.

Various factors such as poor transfer capabilities of the transmission lines, outages of transmission lines, insufficient/lack of reactive reserves, generators being far from load centers, among others are responsible for this ugly trend (Onah et al., 2018; 2019; 2021). Still on a bad note, 15 incidents of voltage collapse in the year 2017 were estimated to cost Nigeria 100 billion dollars. Nigerian manufacturers, small scale businesses and families spent over 3.5 trillion naira per year to power their private generating sets with diesel and petrol. Private households spent 1.56 trillion naira which is equivalent to 13.35 million dollars during that period (Onah et al., 2021).

Various approaches which look at mechanisms that cause voltage collapses and proximities of voltage collapse near the saddle node bifurcation point have been exploited by experts in voltage stability analysis (Onah et al., 2018; 2019,). Unfortunately, the approaches are time consuming. According to (Reis et al., 2006) L-Index and Voltage Collapse Proximity Indicator using IEEE 14-bus were compared but the approach is complex. The approach uses a class of voltage instabilities that corresponds to static bifurcations of load flow equations. However, minimum singular values of the Jacobian matrix and total generated reactive power were calculated as indicators of stability margin, and sensitivity methods were used for reactive support allocation. Improvement in stability margin under progressive loading was investigated on a 39-bus test system for different allocations and amounts of reactive support with reactive generation capabilities taken into account but the approach did not look at the degree of compensation. Be that as it may, the method is time consuming and less accurate in voltage collapse prediction.

Again, the fast voltage stability index is based on the power flow through a single line. It is determined by the measurement of voltage and reactive power of the line. A work that used an improved sensitivity technique to rapidly calculate the real power transfer limit of a defined boundary was exploited by Hong et al. (1997), but the complexity of the approach is boring.

The minimum singular value of the power flow Jacobian matrix was used as a static voltage stability index (Ekwue et al., 1999). The proposed approach utilizes the sparsity of the power flow Jacobian matrix which is complex for a large system.

In the work of Alvarado et al. (1994), the bifurcation geometry for the study of voltage collapse in electric power systems was given attention. The authors utilized the initial direction in state space of dynamic voltage collapse to compute the right Eigenvector of the static power system model. In their view, the normal vector to the bifurcation set in parameter space is a simple function of a left Eigenvector but the approach is less accurate in the voltage collapse prediction. Tamura et al. (1983) showed optimal multiplied introduced to prevent divergence of power flow for ill conditioned and heavily stressed systems. It was further investigated that there is a relationship between multiple load flow solutions and voltage instability by coming up with multilevel criterion. The criterion comprises three criteria which shows voltage instability but cannot be used independently to show whether the system is stable or not. They are of the view that a system is voltage stable if all the criteria indicate voltage stability otherwise voltage instability. However, their approach cannot estimate the maximum loadability of a transmission line.

The new voltage stability index proposed by Samuel et al. (2017) and Samuel et al. (2019) for voltage collapse prediction may give inaccurate predictions owing to the implicit assumption that the resistances of the lines ought to be ignored when they are high.

Mokred et al. (2023) proposed modern voltage stability index for voltage collapse prediction and compared the work with some selected voltage collapse prediction indices. If the authors should take a cursory study of VCPI, they may be shocked with its excellent results and accuracy. The work considered the impedance of the transmission line, the sending and receiving end voltages but the approach is only limited to real power flow along the transmission line.

Thus, this paper relies on the simplicity, reliability and accuracy of VCPI to fill the missing links found on the above literature. Again, the work shows the voltage collapse point of various transmission line of NNG.

2. Materials and Methods

The line data and the bus dased in the simulation were collated from Transmission Company of Nigeria, National Control Center One-line diagram for 45-bus is shown in the MATLAB/SIMULINK Power System Analysis Tool Box (PSAT) was used to carry out the power flow analysis. VCPI is the index employed to predict voltage collapse of Nigeria 330kV Power System. The incidences of voltage collapse from 1987 to 2022 were obtained from (Onah et al., 2018; 2019; 2021,) and are shown in Table I (Samuel et al., 2014).

Table I: Voltage collapse incidences on Nigeria national grid (NNG) from 1987 to 2022

S/N	Year	Partial System Collapses	Total System Collapses	Total Number of Collapses
1	1987	13	20	33
2	1988	8	13	21
3	1989	6	10	16
4	1990	0	14	14
5	1991	1	5	6
6	1992	1	0	0
7	1993	14	5	19
8	1994	4	2	6
9	1995	10	1	11
10	1996	8	2	10
11	1997	13	7	20
12	1998	13	5	18
13	1999	5	4	9
14	2000	6	5	11
15	2001	5	14	19
16	2002	32	9	41
17	2003	39	14	52
18	2004	30	22	52
19	2005	15	21	36
20	2006	10	20	30
21	2007	9	18	27
22	2008	15	25	40
23	2009	20	19	39
24	2010	20	22	42
25	2011	6	13	19
26	2012	8	16	24
27	2013	2	22	24
28	2014	11	2	13
29	2015	2	8	10
30	2016	6	22	28

31	2017	Not Available	Not Available	21
32	2018	11	2	13
33	2019	Not Available	Not Available	11
34	2020	Not Available	Not Available	4
35	2021	Not Available	Not Available	4
36	2022	Not Available	Not Available	7
Total				750

The VCPI index investigates the stability of each line of the system. It is based on the concept of maximum power transferred through a line. The power system is stable if the indicator is less than one, but when the indicator is equal to one or more, the point of voltage collapse is reached. Interestingly, this signifies that near maximum load, extremely large amounts of reactive power are required at the sending end to support an increase in load. The VCPI is thus a very sensitive indicator of impending voltage collapse. The advantage of the use of the index lies in the simplicity, reliability and its ability to give a good indication about the critical power a system can maintain before collapse over the whole region and for all cases studied. The voltage collapse proximity indicator can be given in terms of real power as follow (Salama and Ghariany, 2001).

$$VCPI (P) = \frac{P_a}{P_{amax}} \quad (1)$$

where: P_a is given as the real power flow along the transmission line. P_{max} is given as the maximum real power that can be transferred along the transmission line. In terms of reactive power, the voltage collapse proximity indicator is given as (Salama and Ghariany., 2001).

$$VCPI (Q) = \frac{Q_a}{Q_{a(max.)}} \quad (2)$$

where: Q_a is given as the reactive power flow along the transmission line and Q_{max} is given as the maximum reactive power that can be transferred along the transmission line. The real and the reactive power flow in equations (1) and (2) were obtained using load flow analysis.

However, the maximum power that can be transferred to the receiving end at any instant is given as:

$$P_{a(max.)} = \frac{V_a^2}{Z} \frac{\cos \phi}{4\cos^2 \phi} \left(\frac{\theta - \phi}{2} \right) \quad (3)$$

$$Q_{a(max.)} = \frac{V_a^2}{Z} \frac{\sin \phi}{4\cos^2 \phi} \left(\frac{\theta - \phi}{2} \right) \quad (4)$$

Where Z is the load impedance, V_a is the sending end voltage, ϕ is the phase angle given as $\tan^{-1} \left(\frac{P_a}{P_{amax}} \right)$, θ is the phase angle got from load flow studies. The maximum real and reactive power were obtained from the results of load flow analysis. The data obtained were used to carry out steady state analysis of the power system.

3. Results and discussion

The transfer capabilities of the critical lines are shown in Figure 2 using VCPI. The worst-case transmission line is Katamkpe-Shiroro with the voltage collapse proximity indicator of 2.8684. The transmission line is singled out to investigate the effects of real power variation with VCPI. The effect of the variation of real power transfer with VCPI is shown in Figure 1. The stability of each of the critical lines of the system was investigated based on the concept of maximum power transfer through a line. The power system is in a stable mode if the indicator is less

than one, but when the indicator is equal to one or more, the point of voltage collapse is encountered. The closer the value of VCPI to zero the more the stability of the transmission lines. This implies that at or near maximum load, extremely large amounts of reactive power are required at the sending end to support an incremental increase in load. Thus, VCPI is a very sensitive indicator of impending voltage collapse. The point of voltage collapse was established at the moment the real power transfer got closer to the maximum power transfer capability of the transmission line as can be seen in Figure 2. The Loadability limit of the transmission line is 2.6p.u. The voltage collapse proximity indicator of the transmission line in Figure 2 is approximately 2.8 with the increase in real power flow along the transmission line. The practicability of this model was tested in the 45-bus Nigeria national grid. From the simulations, it was found that out of the 53 transmission lines, 17 transmission lines were overloaded. The most critical transmission line ranked first and has VCPI value of 2.8684 as shown in Figure 1. In Equation 1 as espoused by Figure 2, it is observed that with the increase in real power flow along Katamkpe-Shiroro transmission line, a stage was reached where the maximum load was not able to sustain the load on the transmission line.

Voltage collapse proximity indicator evaluated the NNG and identified areas with very weak transfer capabilities as follow; Kainji-B.Kebbi (1.4667), Egbin-Aja (1.2830), Kaduna-Shiroro (1.1805), Kano-Kaduna (1.5657), Ikeja-Benin (1.0877), Ajaokuta-Benin (1.2683), Onitsha-Benin (2.0482), Onitsha-NewHaven(1.5288), Akangba-Ikeja (1.6667), Calabar-Ikotekpene (2.0700), Benin-Ihovo (2.6273), Omotosho-Benin (1.0035), Owerri-Alaoji (1.105), Katamkpe-Shiroro (2.8684), Katamkpe-Gwagwalada (1.5271), Gombe-Damaturu (2.5412), and Kaduna PQ-Kaduna PV (2.0755) are the transmission lines whose VCPIs are very high. The maximum peak in the Figure 1 shows Katamkpe-Shiroro transmission line with VCPI of 2.8684. Again, the minimum peak at the same Figure 2 shows Omotosho-Benin transmission line with VCPI of 1.0035. The higher the value of VCPI the closer the transmission line to voltage collapse.

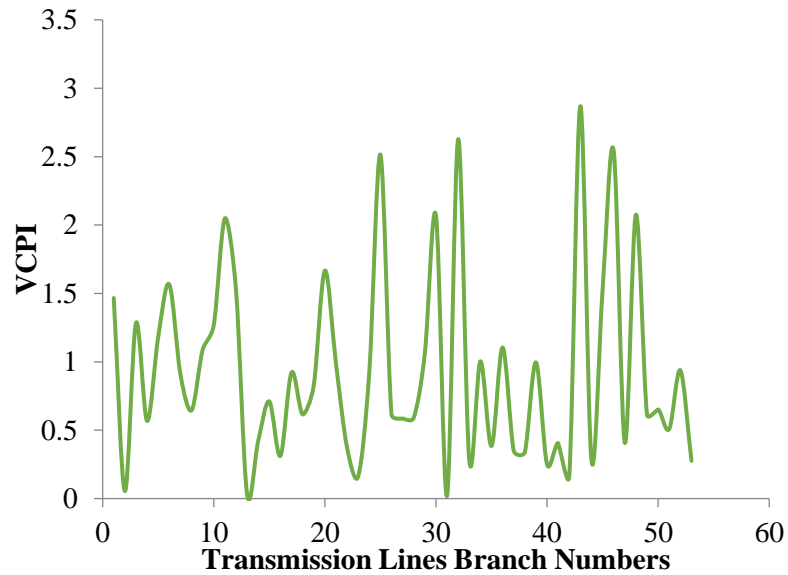


Figure 1: Voltage Collapse Proximity Indicator of 45-Bus NNG

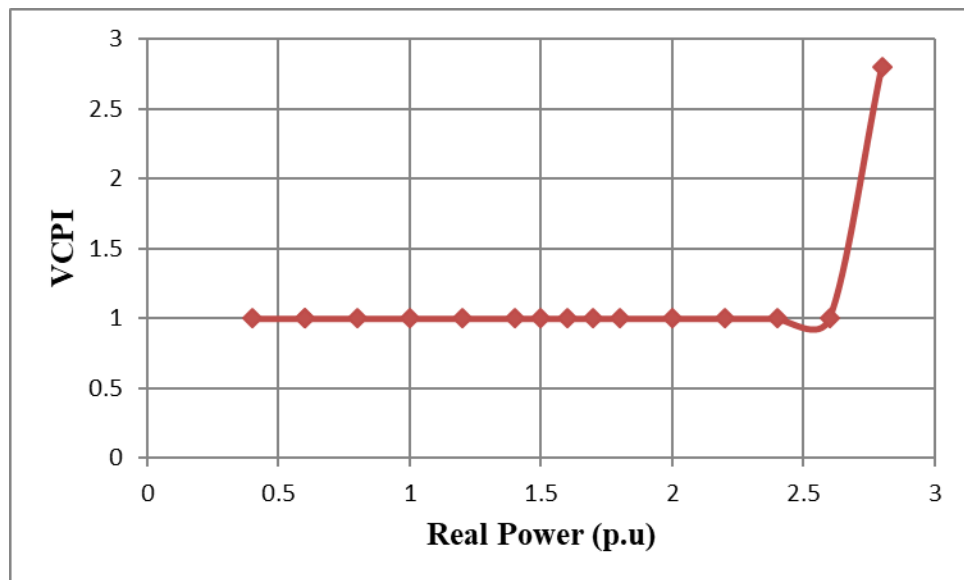


Figure 2: Variation of VCPI of Katamkpe – Shiroro Transmission Line with real power

4. Conclusion

A very simple, reliable and accurate index (VCPI) estimated the collapse point of a very weak transmission system in a 45-Bus NNG. The computation involving the approach identified and ranked areas with very weak transfer capabilities in NNG. The VCPI identified weak boundaries with respect to voltage instability. It also assessed the effects of possible small and large power disturbances. Since Katemkpe-Shiroro transmission line was identified as the most critical transmission line contributing immensely for voltage collapse scenarios in the 45-bus of Nigeria national grid, it is recommended that control system operators should exploit adequate measures to control the impending system collapse. The approach proved to be effective for a practical 45-Bus NNG.

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