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Novel approach for assessing the maximum load capacity of buses within a power transmission network

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ABSTRACT

Achieving a balance between the satisfaction of energy requirements and adherence to environmental and social regulations stipulated in international agreements necessitates the rigorous management of existing electricity systems by electricity network operators, thereby ensuring that thermal and stability limits are not exceeded. Consequently, the assessment of load bus maximum capacity (LBMC) at any given load bus (LB) becomes imperative for ensuring the reliability and efficiency of electricity transmission networks. The extant literature on the subject of assessing LBMC in electrical networks either fails to take into account the combined effects on such networks of their various load points or, if it does, it is computationally intensive. The approach proposed in this paper involves a simplified method for assessing the LBMC for each of the LBs in the network. This is achieved to ensure that the combined effect of increasing the load on each of these buses does not compromise the load planning determined by a given network performance index, either during normal operation or in the event of a malfunction. The findings substantiate the efficacy of the proposed methodology, which facilitates the reliable estimation of LBMC. The reliability of this approach is ensured by the selection of a reliable performance indicator, which in our case is the complex stability index for transmission lines (CSITL).

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1. INTRODUCTION

Heavily loaded power systems are more likely to be affected by voltage instability, which can significantly impact their load bus maximum capacity (LBMC) [1]-[3]. On the other hand, continuous increases in load, coupled with a lack of investment in transmission and generation, mean that power systems are operating very close to their limits capacities [4]. Therefore, the LBMC of each load bus (LB) in the power system is a crucial parameter for the planning of load increasing at each of these LBs. For power systems transmission operating close to their load capacity limit, any requirement to increase the load at the bus level can result in a deterioration in performance. However, assessing the LBMC of a given LB depends on various factors, including the loads connected to other LBs and the maximum line transit capacity (MLTC) of the power system. Consequently, this evaluation is required to consider the repercussions that an augmentation in load would have on the power system's resilience.

The LBMC is typically obtained through successive iterations of the power flow method, involving a gradual increase in system load. This process continues until the power flow method diverges [5]. However, if the objective is to determine the load value at which voltage collapse does not occur in the power system, this approach is irrelevant since voltage collapse may occur before the divergence of power flow. The LBMC can be calculated efficiently using other techniques, such as continuation parameterization methods [6].

Various methodologies for assessing LBMC for buses have been documented in the extant literature. Amjady and Velayati [7] propose a methodology for the evaluation of the LBMC. This proposed method determines the LBMC at the point of voltage collapse using P-V curves. This is achieved by combining the power flow continuation method with a modal analysis of the load flow Jacobians. Ali *et al.* [8] proposed an innovative modification to the classic Newton–Raphson optimal load flow solver for characterizing the system's maximum load. This approach supplements the standard power flow equations with two additional elements. Firstly, an algebraic representation of the maximum and minimum voltage conditions is incorporated. Secondly, the transversality condition is imposed to limit the set of solutions to the boundary of the solvable region. In their study, Gupta *et al.* [9] propose a method for investigating the impact of increased photovoltaic (PV) penetration on the voltage stability of IEEE 14-bus test system. To achieve this, they consider the maximum PV penetration and the system's LBMC. In their article, Gómez-Quiles *et al.* [10] propose a new algorithm for identifying LBMC in power systems. The algorithm in question has been described as both fast and simple. It involves the implementation of bisection searches between feasible and infeasible load flow cases. Zaidan *et al.* [11] delineate the methodology employed to ascertain the LBMC at which voltage collapse occurs, utilizing the continuation power flow technique. Aman *et al.* [12] present a new network reconfiguration algorithm based on maximizing the system's load capacity. The voltage profile of the entire system is enhanced in comparison with the baseline case. Dondariya and Sakravdia [13] propose a new proximity indicator to assess voltage stability and predict the actual critical load of the system, as well as the voltages at various LBs at the critical load point. Acharjee [14] proposes a simple, coded genetic algorithm with real-coded security constraints (SCGA) to identify the maximum loadability limit (MLL) of various IEEE standard test systems. The MLL problem is modelled as an optimization problem that takes security constraints into account. Manohaaran and Gnanambal [15] propose a methodological approach to determining the maximum permissible overall load capacity. This approach optimizes the utilization rate of the load, thereby improving the electrical system's ability to maintain an energy balance when additional loads are added or in an unbalanced scenario. Pequeno dos Santos *et al.* [16] propose an approach to the assessment of composite reliability, utilizing Monte Carlo simulation in conjunction with an analysis of maximum and minimum loads. The maximum load analysis, which is proposed, is also used as part of a cross-entropy optimization procedure to optimize the system's stochastic parameters. Chmielowiec *et al.* [17] present the results of experiments investigating the use of a machine learning approach to estimate nodal load capacity in power systems. They define the concept of nodal load capacity and the methodology for estimating it using a graph neural network. Aghdam and Khoshkhoo [18] proposed method relies solely on the voltage magnitude and the power transmitted through the target bus. It is an effective tool for estimating the loadability margin. Mondal *et al.* [19] propose a novel approach grounded in a mathematical model that can be utilized to ascertain the maximum permissible load limit for multiple LBs in a power system, whilst accounting for safety constraints pertaining to voltage. As part of their study, Yadav and Pal [20] propose a new approach to determining the LBMC of each LB. This approach uses a modified continuous power flow method to calculate a composite index. The composite index is then used to classify LBs and identify the most critical ones.

Some of the methods referenced above require significant computational resources. In some of the above-cited research, the LBMC is assessed at the voltage collapse limit. However, it should be noted that a performance indicator may reach its limit within the network without causing a voltage collapse in certain circumstances. Fonseca *et al.* [21] propose an innovative approach to load capacity analysis. This approach is predicated on the short-circuit power at the LB level. This methodology facilitates the determination of LBMC, contingent on the values of a voltage stability index. Some authors have focused their work on estimating the LBMC at the line voltage stability limit [22]-[25]. Let LBx be the target LB for which the LBMC has to be assessed. Previous references adopt an approach involving gradually increasing the load connected to LBx until the critical stability index value of one of its adjacent lines (LBxAL) is reached. When increasing the load connected to the LBx, it is assumed that the loads on the other LBs in the network will remain constant. The resulting load of this operation then corresponds to the LBMC of LBx. This operation is applied to each of the other LBs individually.

The reliability of this approach is therefore questionable. Examining only the values of the LBxAL stability index could result in the stability index of a given power system line reaching its critical value before one of the LBxAL stability indices reaches its critical value. In this case, it appears that the LBMC of LBx has already been exceeded, which is a shortcoming of this approach. Another shortcoming of this approach is that should an increase in load occur on one or more other LBs in the power system subsequent to the evaluation of the LBMC for LBx, the stability limit will be exceeded, and the earlier evaluation of the LBMC will no longer be valid. If the LBx is to operate close to its LBMC, its load margin would be assessed incorrectly.

It is essential to monitor voltage stability in a power system. Therefore, the LBMC assessment must take this into account. However, in existing studies focusing on this issue [22]-[25], the assessment of LBMC does not take into account the combined effect of increased loads on voltage stability in addition to the shortcomings previously identified. Our study attempts to address these issues by proposing a new methodology to assess the LBMC of each LB in a power system. This methodology ensures that load increases up to a certain level do not affect the power system's operational performance, thus guaranteeing the reliability of load planning for each LB. To achieve this, it introduces a coefficient called the 'global effect load factor (GELF)'. This coefficient allows for more equitable and balanced load planning at each LB level based on the load margin value at each LB, and it can be updated to refine the plan if necessary. This methodology is based on the optimal power flow (OPF) by Newton–Raphson method (NRm) combined with a chosen performance indicator (PI). This article initially uses as the PI, the complex stability index for transmission lines (CSITL) [26]. In [24], the effectiveness and applicability of NCPI are compared with those of the well-known existing indices (Lmn, FVSI, LQP, NLSI, and VSLI) and the results demonstrate the superiority of the NCPI. For this reason, in order to explore the potential advantages of choosing a given voltage stability index over another, the CSITL performance is compared with that of the NCPI.

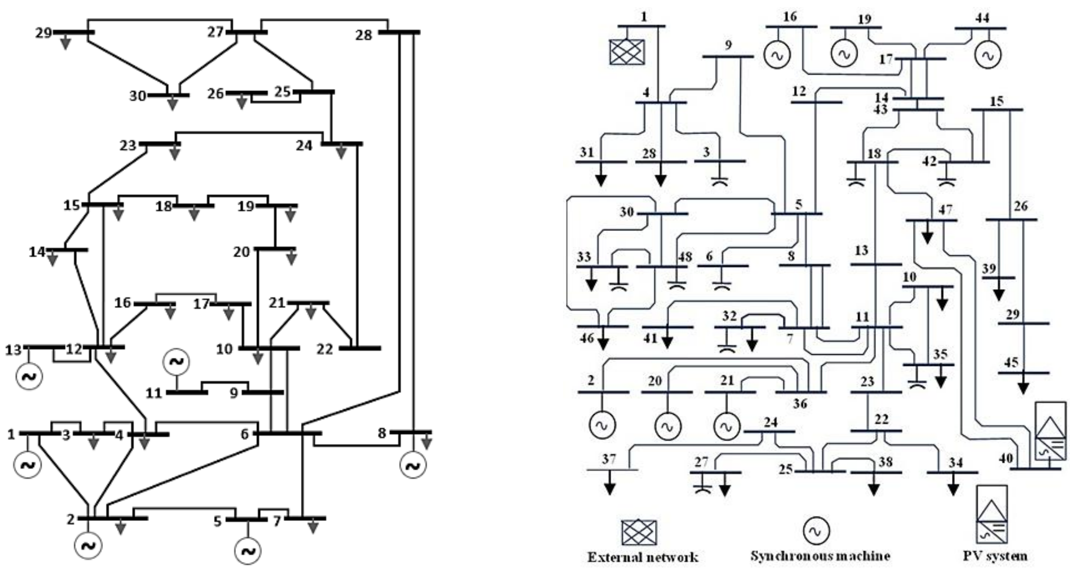
The structure of the present article is outlined as follows: section 2 presents the validation material and the proposed methodology, section 3 covers case studies and simulation results, the analysis of results and discussion, and finally, section 4 is intended for presenting conclusions and perspectives.

2. METHODOLOGY

This section presents the material used and the proposed method of this study. The material used lend credibility to the results obtained using this method.

2.1. Material

This new approach was simulated using both the standard IEEE 30 bus system and a real power transmission network of Niger (PT2N), as illustrated in Figures 1(a) and 1(b), respectively. The data relating to the characteristics of the lines, generators, and buses are taken from [27] for the IEEE 30-bus system. The IEEE 30 bus lines rated transited apparent power values were derived from [28].



(a) (b)

Figure 1. Single-line diagrams of power systems tested: (a) IEEE 30-bus system [27] and (b) PT2N

2.2. Method

Figure 2 presents the flowchart describing the proposed method, which consists of two steps. As described in [23] and [24], the LBMC assessment resulting from a targeted PI constitutes the first phase of the proposed new approach. If the targeted PI is a voltage stability index, for example, its value is examined for each of the lines in the power system. In this study, the evaluation is performed in apparent power. In this case, the LBMC value is referred to as the 'maximum egoistic value of apparent power' for a targeted PI, denoted $S_{max\_eg\_PI}$. The term 'egoistic' is used here because the LBMC evaluation does not take into account the combined effect of increased loads on all LBs on a targeted PI. It is as if the LB for which the LBMC is assessed is the only one where the load increases.

The second phase of this approach involves evaluating the new LBMC for each LB, taking into account the combined effect of the loads present in the power system on a targeted PI. In this case, the LBMC value is referred to as the 'maximum solidary value of apparent power ', denoted $S_{max\_sol\_PI}$. Here, the term ‘solidary’ refers to taking into account the combined effect of all loads in the power system, given their interdependence in terms of their combined effect on a targeted PI. First, determine the solidary apparent power of each LBi related to the targeted PI, denoted S_{sol_IP}(LBi), using (1), where the S_{base}(LBi) corresponds to the base case apparent power of each LBi at the time of evaluation. The α_{PI} parameter is the GELF related to the targeted PI. Its value must be increased gradually from 0 until the target PI reaches its critical value (PI_c). When PI_c reached, the $S_{max\_sol\_PI}$ for each LB is deduced as shown by (2).

$$\begin{bmatrix} S_{sol\_PI}(LB_1) \\ S_{sol\_PI}(LB_2) \\ \vdots \\ S_{sol\_PI}(LB_n) \end{bmatrix} = \begin{bmatrix} S_{\text{base}}(LB_1) \\ S_{\text{base}}(LB_2) \\ \vdots \\ S_{\text{base}}(LB_n) \end{bmatrix} + \alpha_{PI} \begin{bmatrix} S_{\max\_eg\_PI}(LB_1) - S_{\text{base}}(LB_1) \\ S_{\max\_eg\_PI}(LB_2) - S_{\text{base}}(LB_2) \\ \vdots \\ S_{\max\_eg\_PI}(LB_n) - S_{\text{base}}(LB_n) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} S_{max\_sol\_IP}(LB_1) \\ S_{max\_sol\_IP}(LB_2) \\ \vdots \\ S_{max\_sol\_IP}(LB_n) \end{bmatrix} = \begin{bmatrix} S_{base}(LB_1) \\ S_{base}(LB_2) \\ \vdots \\ S_{base}(LB_n) \end{bmatrix} + (\alpha_{IP}|_{IP=IP_c}) \begin{bmatrix} S_{max\_eg\_IP}(LB_1) - S_{base}(LB_1) \\ S_{max\_eg\_IP}(LB_2) - S_{base}(LB_2) \\ \vdots \\ S_{max\_eg\_IP}(LB_n) - S_{base}(LB_n) \end{bmatrix} \quad (2)$$

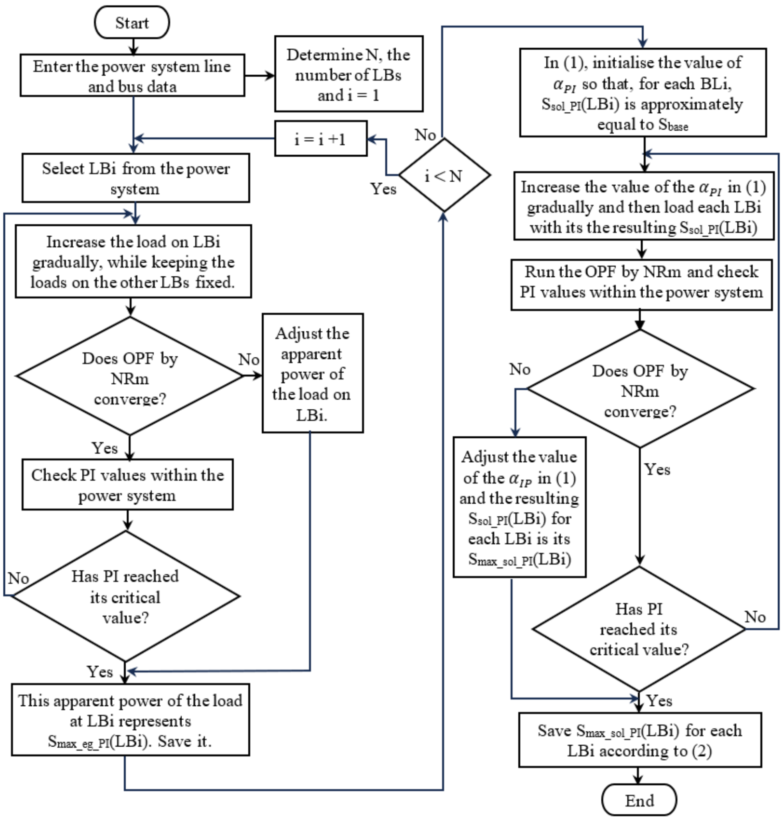


Figure 2. Flowchart of the proposed method

Once the $S_{max\_sol\_PI}$ has been evaluated for each of the LBs, the resulting solidary load margin LM_{sol_PI} can be determined using (3). The important aspect to note with $S_{max\_sol\_PI}$ is that, even though GELF appears as the load factor used by other existing studies, taking into account the gap between $S_{max\_sol\_PI}$ and S_{base} is the new consideration. Moreover, it is this consideration of the gap between $S_{max\_eg\_PI}$ and S_{base} that justifies the 'solidary' qualifier attributed to $S_{max\_sol\_PI}$, because the greater this gap is for a given LB, the greater its LM_{sol_PI}, and the smaller it is, the lower its LM_{sol_PI}.

Based on a simple transport line model (see Figure 3), the CSITL stability index and its module are expressed by (4) and (5), respectively. Similarly, the NCPI formulation (6) is derived from this model.

$$LM_{sol\_PI} = S_{max\_sol\_PI}(LB_i) - S_{base}(LB_i) \quad (3)$$

$$CSITL = \frac{4}{V_s^2}\left(\frac{RP_r}{cos^2(\theta-\delta)} + j\frac{XQ_r}{sin^2(\theta-\delta)}\right) \quad (4)$$

$$|CSITL| = \frac{4}{V_s^2}\sqrt{\left(\frac{RP_r}{cos^2(\theta-\delta)}\right)^2 + \left(\frac{XQ_r}{sin^2(\theta-\delta)}\right)^2} < 1 \quad (5)$$

$$NCPI = \frac{4Z^2}{XV_s^2}\left(\frac{4Z^2P_r^2}{XV_s^2} + |Q_r|\right) < 1 \; with \; Z = \sqrt{R^2 + X^2} \quad (6)$$

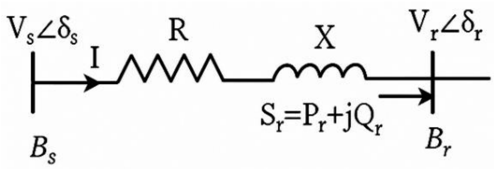


Figure 3. Simple transport line model

3. CASE STUDIES AND SIMULATION RESULTS

3.1. Evaluation of Smax_sol: case of the IEEE 30 bus system

In this case study, the apparent powers $S_{max\_eg\_PI}$ and $S_{max\_sol\_PI}$ are evaluated at each LB and the load margins LM_{sol_CSITL} and LM_{sol_NCPI} are deduced. The GELF obtained by taking CSITL as monitored PI, is $\alpha_{CSITL} = 0.075$, and that obtained by taking NCPI as the PI to monitor, $\alpha_{NCPI} = 0.1554$. The simulation results obtained are presented in Table 1. These results obtained reveal that the value of $S_{max\_eg\_PI}$ or $S_{max\_sol\_PI}$ varies depending on the PI monitored during the evaluation, even for the same bus. This can be seen by looking at LB3: the value of $S_{max\_eg\_CSITL}$ obtained is 113 MVA, which is significantly lower than the value of $S_{max\_eg\_NCPI}$ (476 MVA). However, this difference is less significant for the same LB between $S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$, as illustrated by Figure 4. As can be seen from Table 1, the values of $S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$ are respectively 10.96 MVA and 76.24 MVA. The values of $S_{max\_eg\_NCPI}$ and $S_{max\_sol\_NCPI}$ are respectively higher than those of $S_{max\_eg\_CSITL}$ and $S_{max\_sol\_CSITL}$ at each LB. At the level of each LB, the results obtained for LM_{sol_CSITL} and LM_{sol_NCPI} show significant differences between these two stability indices. The findings from Table 1 indicate that the lowest LM_{sol_CSITL} value is recorded at LB26 (2.14 MVA) and the highest at LB10 (17.03 MVA). Furthermore, the lowest LM_{sol_NCPI} value is recorded at the same LB26 (5.1 MVA), while the highest is recorded at LB3 (73.55 MVA). According to the CSITL and the NCPI, the weakest and most powerful LBs are presented as such (bus 26 and bus 10, respectively). One might naturally assume that one of the two indices is more reliable, since the impact on stability should be the same for the same LB. Does the fact that LM_{sol_NCPI} is higher than LM_{sol_CSITL} at each LB level imply that NCPI is more reliable than CSITL for assessing LBMC? The idea behind the $S_{max\_sol\_PI}$ assessment is to determine the maximum load that can be applied simultaneously to each LB of the power system at the PI criticality limit. However, this must not have an adverse effect on the system's other performances.

In order to evaluate the effectiveness of the two indices used in this study, the impact of simultaneously applying $S_{max\_sol\_CSITL}$ and then $S_{max\_sol\_NCPI}$ on the bus voltage profile and the apparent power transmitted through lines in the IEEE 30-bus system is analysed. The results obtained are presented in Figures 5(a) and 5(b). As demonstrated in Figure 5(a), the application of $S_{max\_sol\_NCPI}$ on each LB results in the collapse of the voltage of the majority of buses. Conversely, the application of $S_{max\_sol\_CSITL}$ on each LB results in a marginal alteration to the bus voltage profile. Figure 5(b) shows that, unlike the application of $S_{max\_sol\_CSITL}$ to each LB, the power transmitted through the lines resulting from the application of $S_{max\_sol\_NCPI}$

to each LB is greater than the nominal transmission capacity of the lines. Applying $S_{max\_sol\_CSITL}$ has a marginal impact on both the bus voltage profile and the apparent power transmitted through the lines. Conversely, the impact of applying $S_{max\_sol\_NCPI}$ to these two operational performances is very significant.

Table 1. IEEE 30 bus system case study simulation results

LB number	S_{base} (MVA)	$S_{max\_eg\_CSITL}$ (MVA)	$S_{max\_eg\_NCPI}$ (MVA)	$S_{max\_sol\_CSITL}$ (MVA)	$S_{max\_sol\_NCPI}$ (MVA)	LM_{sol_CSITL} (MVA)	LM_{sol_NCPI} (MVA)
LB 3	2.68	113.00	476.00	10.96	76.24	8.27	73.55
LB 4	7.77	106.00	444.00	15.13	75.56	7.37	67.79
LB 7	25.27	92.00	352.00	30.28	76.05	5.01	50.77
LB 10	21.79	248.80	253.00	38.81	57.72	17.03	35.93
LB 12	13.48	170.00	200.00	25.22	42.46	11.74	28.99
LB 14	6.40	97.50	113.00	13.24	22.97	6.83	16.57
LB 15	8.57	115.00	177.00	16.55	34.75	7.98	26.17
LB 16	3.94	85.75	138.00	10.07	24.77	6.14	20.83
LB 17	10.71	138.00	185.00	20.25	37.79	9.55	27.09
LB 18	3.32	73.00	84.00	8.55	15.86	5.23	12.54
LB 19	10.09	102.50	117.00	17.02	26.70	6.93	16.61
LB 20	2.31	98.00	125.00	9.49	21.37	7.18	19.07
LB 21	20.78	140.00	239.00	29.72	54.69	8.94	33.91
LB 23	3.58	71.40	141.00	8.66	24.93	5.09	21.36
LB 26	4.19	32.75	37.00	6.33	9.29	2.14	5.1
LB 29	2.56	42.00	48.00	5.52	9.62	2.96	7.06
LB 30	10.77	47.25	53.00	13.51	17.33	2.74	6.56

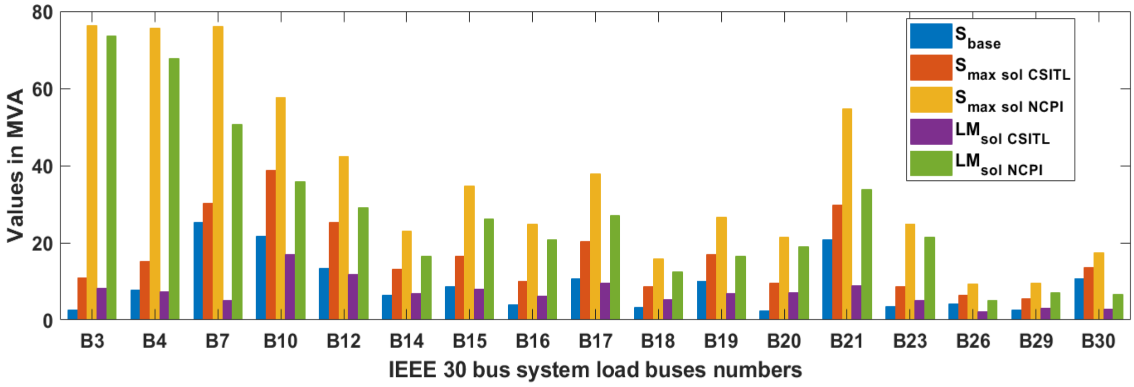
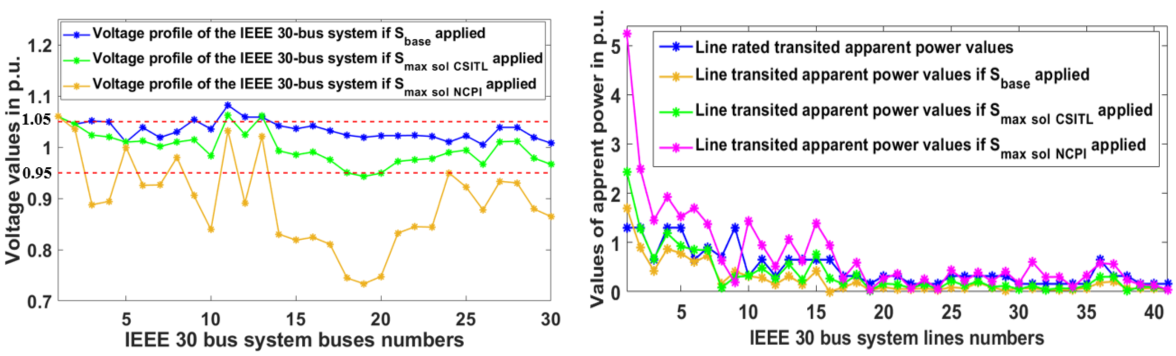


Figure 4. Maximum load capacities ($S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$) and load margins (LM_{sol_CSITL} and LM_{sol_NCPI}) of the LBs



(a) (b)

Figure 5. Illustration of the impact of applying the S_{base}, the $S_{max\_sol\_CSITL}$, and then the $S_{max\_sol\_NCPI}$ to each LB in the IEEE 30-bus system on: (a) the voltage profile and (b) the transited power by the lines

3.2. Evaluation of Smax_sol: case of the PT2N

This subsection is reserved for assessing the apparent powers $S_{max\_eg\_PI}$ and $S_{max\_sol\_PI}$ and the load margins LM_{sol_CSITL} and LM_{sol_NCPI} are deduced for PT2N LBs, for which CSITL and NCPI are used again. The GELF obtained by taking the CSITL as the monitored PI is $\alpha_{CSITL} = 0.1218$, and the GELF obtained by taking the NCPI as the monitored PI is $\alpha_{NCPI} = 0.128$. The simulation results are presented in Table 2.

In addition to the observation that the values of $S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$ are comparatively low, the results obtained demonstrate the same observations as for the IEEE 30 bus system case study. However, it is notable that the load margins (LM_{sol_CSITL} and LM_{sol_NCPI}), resulting from CSITL and NCPI monitoring are of the same order of magnitude, and in some cases even equal, for a number of LBs. Even if the values are not equal, a consistent assessment is made for several LBs with both CSITL and NCPI monitoring. For example, LB33 has the highest $S_{max\_eg\_CSITL}$ value (93.79 MVA), as well as the highest $S_{max\_eg\_NCPI}$, $S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$ values (142.93 MVA, 66.98 MVA, and 73.46 MVA, respectively). LB31 has the highest LM_{sol_CSITL} and LM_{sol_NCPI} values (8.69 and 12.49 MVA, respectively), while LB34 has the lowest (0.91 and 0.92, respectively). The results of this case study are illustrated in Figure 6. As in the previous case study, the impact of simultaneously applying $S_{max\_sol\_CSITL}$ and then $S_{max\_sol\_NCPI}$ on the bus voltage profile and the apparent power transmitted through lines in PT2N is analysed. The results obtained are presented in Figures 7 and 8. The results show that applying $S_{max\_sol\_CSITL}$ to each of the LBs proved more reliable than applying $S_{max\_sol\_NCPI}$. Applying $S_{max\_sol\_CSITL}$ only degraded the voltage profile at the LB22, LB24, and LB25 load buses. In contrast, the application of $S_{max\_sol\_NCPI}$ led to a significant voltage collapse for most buses. The apparent power transit by each line, resulting from the application of $S_{max\_sol\_CSITL}$, remains below the nominal values. Conversely, the application of $S_{max\_sol\_NCPI}$ leads to apparent power transit values that exceed the nominal values through certain lines.

Table 2. PT2N case study simulation results

LB number	S_{base} (MVA)	$S_{max\_eg\_CSITL}$ (MVA)	$S_{max\_eg\_NCPI}$ (MVA)	$S_{max\_sol\_CSITL}$ (MVA)	$S_{max\_sol\_NCPI}$ (MVA)	LM_{sol_CSITL} (MVA)	LM_{sol_NCPI} (MVA)
LB10	31.19	58.50	106.70	34.51	40.85	3.33	9.67
LB27	4.26	21.54	22.50	6.36	6.59	2.11	2.22
LB28	7.85	79.00	109.90	16.51	20.91	8.67	12.43
LB 31	13.33	84.70	115.90	22.03	26.46	8.69	12.49
LB 32	23.67	54.69	78.50	27.45	30.69	3.78	6.68
LB 33	63.26	93.79	142.95	66.98	73.46	3.72	9.71
LB 34	1.78	9.25	9.30	2.69	2.74	0.91	0.92
LB 35	28.12	57.27	105.45	31.67	38.02	3.55	9.42
LB 37	4.45	11.50	11.50	5.30	5.35	0.86	0.86
LB 38	1.56	7.20	7.25	2.24	2.28	0.69	0.69
LB 39	0.89	9.40	10.00	1.93	2.06	1.04	1.11
LB 41	13.69	40.70	79.00	16.98	22.05	3.29	7.95
LB 45	1.78	17.30	17.25	3.67	3.76	1.89	1.88
LB 46	12.11	39.58	88.60	15.46	21.90	3.35	9.32
LB 47	16.69	45.25	96.80	20.17	26.94	3.48	9.76

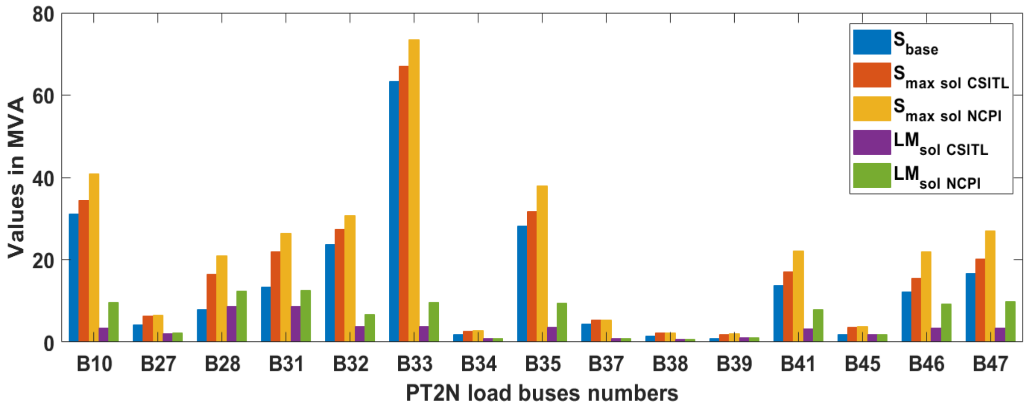


Figure 6. Maximum load capacities ($S_{max\_sol\_CSITL}$ and $S_{max\_sol\_NCPI}$) and load margins (LM_{sol_CSITL} and LM_{sol_NCPI}) of the LBs

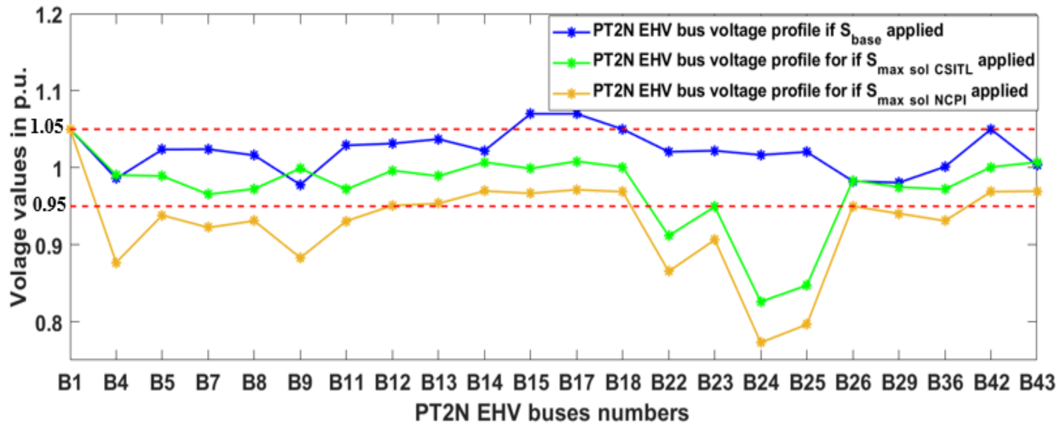


Figure 7. Illustration of the impact of applying the S_{base}, the $S_{max\_sol\_CSITL}$, and then the $S_{max\_sol\_NCPI}$ to each LB in the PT2N on the voltage profile

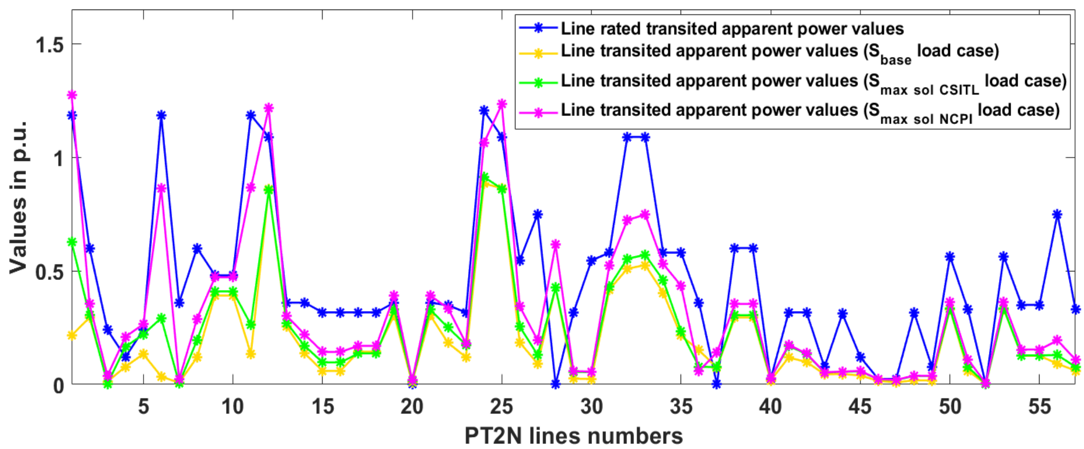


Figure 8. Illustration of the impact of applying the S_{base}, the $S_{max\_sol\_CSITL}$ and then the $S_{max\_sol\_NCPI}$ to each LB in the PT2N on the transited power by the lines

4. ANALYSIS OF RESULTS AND DISCUSSION

Since the proposed LBMC evaluation method takes into account the combined effect of the increase in the load of each LB, variations in these loads will not have an immediate impact on the $S_{max\_sol\_PI}$ after evaluation, unless the power system is close to its capacity limit. This depends on the target PI being monitored. This method is innovative because it does not require monitoring the dynamics of load changes on each bus. Provided that the $S_{max\_sol\_PI}$ of a bus is not exceeded, the PI will not degrade. As the available load margin for each LB is known, it is possible to monitor the risk of exceeding $S_{max\_sol\_PI}$. Provided the load increase for each LB remains within its margin, regardless of the dynamics of this increase, the PI in question will not deteriorate. However, all of this depends on how reliable the PI is. This method is particularly useful for the power systems operating close to their capacity limits, as it enables at-risk PIs to be monitored by determining the $S_{max\_sol\_PI}$ and LM_{sol_PI} of each LB relative to each targeted PI. Once these values are known, it is simply a matter of monitoring them to predict the degradation trend of the targeted PIs.

This method enables LBs to be characterized as either close to or distant from their $S_{max\_sol\_PI}$, depending on the results obtained. This proximity is relative. For instance, in the IEEE 30 bus system, LB26 has a LM_{sol_CSITL} of 2.14 MVA, representing 51.07% of its S_{base} (4.19 MVA). Therefore, if this bus is located in an area where the load evolution dynamics are correlated with S_{base} (rural area), it is not the bus closest to its $S_{max\_sol\_CSITL}$. Conversely, if we consider LB7, its LM_{sol_CSITL} is 5.01 MVA, representing 19.8% of its S_{base} (25.27 MVA). If it is located in an area where load evolution dynamics are also correlated with S_{base} (e.g. an urban area), then it is closer to its $S_{max\_sol\_CSITL}$ than B26.

With regard to the results obtained, observation of the load margins at the various LBs reveals that the LBs in the IEEE 30 bus system are located further from their maximum $S_{max\_sol\_CSITL}$ than those in the TP2N. It is noteworthy that the voltage profile resulting from the application of $S_{max\_sol\_CSITL}$ for each LB proves to be more effective for IEEE 30-bus system buses than for TP2N EHV buses. This is not the case when $S_{max\_sol\_NCPI}$ is applied for each LB, whether in the IEEE 30-bus system or in TP2N, which causes a very significant collapse in bus voltage. The results also reveal that, unlike applying $S_{max\_sol\_NCPI}$ for each LB, applying $S_{max\_sol\_CSITL}$ for each LB did not cause any line overload for either system, especially for the IEEE 30-bus system.

5. CONCLUSION

This article introduces a novel method for assessing the maximum load capacity of buses within a power system. The relevance of this approach was assessed through simulations of the IEEE 30-bus system and a real network (PT2N). Unlike other existing methods, this approach is simple to implement. It makes it possible to assess the likelihood of an increase in load on a bus affecting a power system performance index over a given period, based on the available load margin (LM_{sol_PI}). This is because it enables the LM_{sol_PI} to be determined for each loaded bus. Provided the load on each of these buses remains within LM_{sol_PI}, $S_{max\_sol\_PI}$ remains valid. This enables the load to be planned according to a given performance objective, with the time horizon depending on the LM_{sol_PI} and the load evolution dynamics at each loaded bus. This method is useful for monitoring power system whose buses are close to their maximum load capacity relative to a target PI. It involves updating the GELF parameter (α_{PI}) at appropriate intervals. The integration of this parameter with contemporary artificial intelligence techniques has the potential to enhance the efficacy of a given PI prediction deterioration within a power system context.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors of this article formally affirm that their contributions are not associated with any material or financial interests.

DATA AVAILABILITY

The data relating to the IEEE 30 bus system lines and bus that support the findings of this study are openly available in [Illinois Center for a Smarter Electric Grid] at [26]. The data relating to IEEE 30 bus system lines rated transit capacity values, which support the findings of this study, are openly available in 10.1088/1742-6596/2319/1/012010. Derived data relating to PT2N supporting the findings of this study are available from the corresponding author, [MG], on request.

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