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Optimal instantaneous prediction of voltage instability due to transient faults in power networks taking into account the dynamic effect of generators

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Abstract: Changes in consumption and changes in the structure of the system always occur in each power system. One of the effects of these changes can be the instability of the system voltage. When voltage is unstable, their performance is in conditions of power fluctuations after large errors occur. Determining the voltage stability of traditional methods is time consuming and does not have the necessary efficiency for instantaneous monitoring. In this paper, an index based on the changes of two indices of frequency deviation and frequency response of inertia in the time after the occurrence of perturbation is presented, which has the ability to detect the occurrence of instability and at the same time high speed timely estimation of voltage instability in the power system. In addition, this indicator has been used to determine the appropriate time to start load removal (voltage reduction load). All simulations are performed on the IEEE 33-bus network in DlgSILENT software, the results of which indicate that the proposed index has a very low computational load. Because the proposed method for instantaneous voltage instability prediction does not depend on

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Authors of the manuscript working the various research activities based on the renewable energy integration, utilization of power electronics converters in renewable energy integration, smart grid technologies, micro grid development, renewable energy system’s modeling and development, implementation of artificial intelligence techniques in smart electrical grids and power system planning, mitigation of power quality issues, fault analysis, application of meta heuristic techniques in power system, power system reliability and stability.

In this manuscript authors presented optimal instantaneous prediction of voltage instability due to transient faults in power networks taking into account the dynamic effect of generators. This research is very much critical for the stable and reliable real time operation of the power system. Recent smart grid technology, phasor measure units are utilized in this research to perform the fault analysis.

PUBLIC INTEREST STATEMENT
Because of, there are changes in power consumption in each power system and also changes in the structure of the system itself, moment-by-moment monitoring and estimation of voltage stability of power systems based on phasor measurement unit (PMU) based algorithm is the option, studied in this paper. The inertial frequency response is provided in the time after the occurrence of the perturbation, which has the ability to detect the occurrence of instability and at the same time the high speed of timely estimation of voltage instability in the power system. In addition, this indicator has been used to determine the appropriate time to start load removal (voltage reduction load). The results indicate that the proposed method for momentary prediction of voltage instability is not dependent on the network structure and load model and does not require any threshold value. Therefore, the proposed index has a very low computational load. The proposed method can be considered an interesting option for online and practical applications.
the network structure and load model and does not require any threshold value. Therefore, the proposed index has a very low computational load. These advantages make the proposed method an interesting option for online and practical applications.

**Subjects:** Artificial Intelligence; Power & Energy; Electrical & Electronic Engineering

**Keywords:** Transience; fault forecasting; fault occurrence; induction generator

1. Introduction

Due to the increase in load in power networks and restructuring in power systems, these systems are usually operated within their stability limits. This has led to widespread turmoil and power outages in power systems in recent years. There are several factors involved in the occurrence of these blackouts, among which voltage instability has been suggested as one of the main reasons for these blackouts. Research shows that in many cases such incidents can be prevented. This requires real-time monitoring and the use of appropriate control and protection systems in the power system. To do this, you must use devices that have the ability to measure the required information in real time. Phasor measurement units with high measurement rate have created this capability in the network. The occurrence of a disturbance causes the voltage level to decrease and become uncontrollable. Voltage stability indicators are scalars that examine changes in power system parameters. These indicators, which can be based on static analysis or dynamic models of the power system, have the ability to determine critical buses, evaluate the stability of each line connected between two buses, or evaluate the stability margin of the system.

1.1. Literature review

Many researches have been proposed in this regard that can be (Gorbunova & Anisimov, 2020; Nasab et al., 2022; Y Shu et al., 2020) that with The use of system phasor information has been investigated for voltage stability, he noted. Also in (Kapeller et al., 2021; Shinde & Ardhapurkar, 2016; Tahir et al., 2021), considering that voltage stability is evaluated both locally and extensively, two methods based on local and extensive information have been proposed in which neural networks have been used to predict voltage stability. In (Nasab et al., 2022) a method based on local information is presented and an attempt is made to solve the problems of traditional methods and also a new indicator for real-time monitoring of voltage stability is presented. Also, in the proposed method, based on extensive information, an attempt has been made to resolve ambiguities in traditional methods and provide practical solutions for using the method in real power networks. In (Guo et al., 2015; Ransient energy, 2010; H. Shu et al., 2011) to determine the limit of voltage stability in the event of possible events in the network, a method is provided to do this with high accuracy. Under the conditions that a limited number of phasor measuring units are available, in other words, the optimal placement of phasor measuring units has been done with the aim of more accurately calculating the voltage stability limit. Also, in (Zand et al., 2020) A zero value of the reduced Jacobin matrix means that the system is at the voltage instability limit. The voltage collapse position of a stable system can be predicted by evaluating the minimum positive eigenvalues. The amplitude of each eigenvalue, at least, is the magnitude of how close the system is to voltage breakdown. The time required for calculations in this index in large networks, led to other indicators to test the stability of the network voltage (M Zand et al., 2019). In (Azimi Nasab et al., 2021) provided an indicator for estimating the proximity to the load limit. To calculate this index, first the tonnage equivalent of the power system is obtained from the bus in question, and then by calculating the load admittance changes, voltage and apparent power changes, the index size can be calculated. This index has a positive value in the stable voltage zone, a zero value in the instability region and a negative value in the unstable region. The voltage drop load is the last resort to counteract the voltage instability in the power system. Various papers have been presented in this field, for example, (Tripathi et al., 2012) in this method, first by calculating the tonnage equivalent circuit of each bus, a coefficient is obtained that is used to calculate the ratio of load impedance to tonnage impedance. For this reason, it is suggested in this paper that when the ZL/Zth ratio is less than the range of 2.5–1, the applying load
shedding should begin. In (Mohammad Zand et al., 2020) presented a method for optimal applying load shedding in the power system, in which two factors are proposed to remove the optimal load: i: The load removed from the system should have a great impact on improving voltage stability. ii: times that it is removed from the system should be low cost. Various indicators have been considered in the authorities to check the detection of short-term voltage instability (Rohani et al., 2019) Voltage curves after perturbation are considered as criteria for investigating and diagnosing short-term voltage instability (Tightiz et al., 2020) In (Phadke & Thorp, 2008) the Maximum Lyapunov Exponents (MLE) method is used as a tool to show the convergence or divergence of the path of voltage changes of load bars, in order to predict short-term voltage instability. The size of the window required to calculate the MLE plays a very important role in the accuracy and speed of operation of this method, so that the small size of the window leads to high speed in predicting but reduced performance stability and stable items are recognized as unstable and large window size. Although it increases security, it slows down the forecast. Also, the size of the optimal length for the window depends on the type and severity of the perturbation and the network structure (Sahani & Dash, 2019), which makes it impossible to implement the method in real-time stability evaluation conditions. Artificial intelligence-based methods have also been introduced in (Izykowski et al., 2011) with the aim of monitoring short-term voltage instability. In these methods, various tools such as neural network have been used to distinguish steady state from unstable. Although methods based on artificial intelligence have a high speed, but the degree of accuracy of their performance depends on the amount of training in different conditions such as various operating conditions and changes in network topology. Tuning equivalent circuit as a simplified model of a large power system is an analytical method that has been used to determine the state of voltage stability in various references such as (Ghazizadeh-Ahssaei, 2020). In methods based on the calculation and estimation of tonnage equivalent circuit parameters, since the generator dynamics are neglected and only the load dynamics are considered, under modes where the operating conditions of the generators change, the simplified model will not be accurate enough (Eskandari & Savkin, 2020). In the methods presented in (Mohamedi et al., 2018) with the aim of investigating short-term voltage instability, it is assumed that only this type of instability is possible in the network and transient instability is not considered. Conversely, the same method has been adopted in (Fazaeli et al., 2022; Madhumita & Debnath, 2020; Mishra & Yadav, 2018; Nale & Biswal, 2016; Nale et al., 2019; Nasab et al., 2021; Rajeswary et al., 2016) the proposed methods to investigate transient instability. However, due to the intertwining of these two types of instability, a single method is needed to be able to distinguish between steady state and unstable state, whether the dominant instability is transient or short-voltage.

According to recent research and above, it can be seen that the lack of dynamic effect of generators in simplified models to check the stability of short-term voltage, in the event of significant changes in the operating conditions of generators, will lead to inaccuracies in the result. Also, ignoring the load dynamics may lead to incorrect conclusions about the stability of the power system. In order to improve the stability of the power system, both transient stability and short-term voltage must be considered simultaneously; otherwise, corrective action may improve one type of this instability and put the other type in a critical position. Also according to recent studies, following the occurrence of perturbations in the network, an imbalance between load and output occurs, which will cause frequency deviation. In this paper, using the frequency measured by PMUs installed in generator bus and then calculating the inertial frequency response (IFR) and frequency deviation and finally examining how these two indicators change, an algorithm to predict short-term voltage instability in the form of system integrity protection scheme (SIPS) is presented. In the following, the structure of the article is as follows: In the second part, the System Integrity protection scheme is described. In the third part, the proposed algorithm is examined. In the fourth part, the results are simulated. Is discussed and finally presented in the fifth section.

2. Conventional system integrity protection scheme (SIPS)
Conventional protection equipment is not able to maintain the integrity of the entire system due to the use of local data, so in order to take appropriate control measures in case of system
emergency, it is necessary to design a comprehensive protection system that can assess the
condition of the whole system. In recent years, to solve this problem, system integrity protection schemes called SIPS have been used. SIPS can be introduced as an automatic protection system to detect abnormal or predetermined system conditions or disturbances that, with early detection, maintain the stability of the system in an emergency (Rohani et al., 2019).

The occurrence of perturbations in the power system can be observed in various ways, such as the use of measuring voltages and currents or the operation of a relay against the occurrence of this perturbation. These signals can be used as SIPS input and processed using decision elements. If the criteria set for the decision exceeds the set level, the predetermined actions will be implemented. The structure of this process is shown in Figure. 1.

SIPS designs use different structures such as flat, hierarchical and centralized (Mohammad Zand et al., 2020). In a centralized structure, as the name implies, and Figure 2, all information is collected from the monitored posts and locations and transferred to a central location, where data processing and decision-making take place. In the algorithm presented in this paper, a centralized SIPS structure is used.

3. System integrity protection scheme
The proposed scheme is based on the frequency of network generators, which assumes that these algorithms are available by PMUs located in the network generator bus. In this section, first, the stability assessment plot presented in this article is introduced, and then, the steps of the proposed algorithm are described step by step.

The condition for activating the proposed algorithm is the value of receiving the signal \(\Delta F_i\) frequency change relative to the network frequency (according to the relation (1)).
\[ \Delta F_i(\Delta t) = f_i(\Delta t) - 1 \quad (1) \]

In relation to \( \Delta F_i(\Delta t) \) represents the output frequency of the generator \( I \). Simultaneously with the activation of the algorithm, the signal \( f_i(\Delta t) \) and the signal \( \Delta P_i \) IFR are calculated according to relation (2) at each time step.

\[ \Delta P_i(\Delta t) = \frac{2H_i}{f_0} S_{NI} \frac{df_i(\Delta t)}{dt} \quad (2) \]

And in relation (2), \( S_{NI}, H_i \) and \( f_0 \) represent inertia, apparent rated power of generator \( i \) and rated frequency, respectively. By plotting the changes of the two signals \( \Delta P_i \) and \( \Delta f_i \) relative to each other, a short-term voltage stability evaluation plot (SAP) is created. The step f proposed algorithm based on the detection of 2 position in SAP are as follows:

(i) **Position \( P_1 \):** Due to the trend of frequency changes, there may be two modes for position \( P_1 \):

**First case:** position \( P_1 \) is the local position as shown in Figure 3(a), the frequency decreases after the ascending process, so this position is a relative maximum) or the maximum in the steady state (and the frequency derivative in position \( P_1 \) is a value close to zero. As shown in Figure 3(b) the position where \( \Delta f_i \) starts to decrease from that moment and the value of \( \Delta P_i \), which is proportional to the frequency derivative, is close to zero, the position \( P_1 \) is determined.
Second case: position $P_1$ is the position where, as shown in Figure 4(a), the frequency has a turning point while it is ascending. This turning point changes the polarity of the frequency derivative and as it is shown that the path of change along the $P_1$ axis, which depends on the value of the frequency derivative, changes after position $P_1$.

(i) Position $P_2$: If position $P_1$ is a relative maximum position (first case, the frequency decreases after this position). Where, as shown in Figure 3(b), this decreasing trend stops and the frequency increases again, position $P_2$ is determined. Since this position is an extreme position, the frequency derivative $\Delta P_i$ is a value close to zero.

4. Proposed algorithm
In the following, the steps of the proposed algorithm are described.

- The first step: selection of candidate generators (in online conditions):

with the occurrence of perturbations in the network, the generators that are electrically the shortest distance to the perturbation site, receive the greatest impact of perturbation (Phadke & Thorp, 2008; Sahani & Dash, 2019; Tightiz et al., 2020), so that due to the difference in power Mechanically and electrically, the frequency increases abruptly, and the greater the slope of this increase for the generator than other generators, indicates that the generator is more affected by the perturbation. Its $|\Delta P_i|$ mean has the highest value in the first 5 time steps after the disturbance occurs, and among the other generators, generators whose mean $\Delta P_i$ value is more than half of the $|\Delta P_j|$ generator in the mentioned time interval are selected. Are selected as Candida generators and then their $\Delta P_i - \Delta F_i$ variations are used to predict short-term voltage instability.
The second step: predicting the occurrence of short-term voltage instability (in online condition:)

In the proposed algorithm, three conditions are checked to predict the occurrence of short-term voltage instability. Two of these conditions relate to the two positions $P_1$ and $P_2$ described in Section 3. Each of these conditions is described below.

(A) $P_1$ constrain: If the position of $P1$ conforms to the second condition described in the section 3, the proposed algorithm in the same position in terms of time predicts the occurrence of short-term voltage instability

| Security (%) | Reliability (%) | Unstable Predicted | Stable Predicted | Status   | period of time fault (cycle) |
|--------------|-----------------|--------------------|------------------|----------|-----------------------------|
| 100          | 100             | •                  | 133              | Stable   | 5                           |
|              |                 | 37                 | 0                | Unstable |                             |
| 100          | 100             | •                  | 110              | Stable   | 6                           |
|              |                 | 60                 | 0                | Unstable |                             |
| 100          | 100             | •                  | 95               | Stable   | 7                           |
|              |                 | 75                 | 0                | Unstable |                             |

Figure 6. Outline of the proposed algorithm.
Figure 7. Single-line diagram of IEEE 39-bus system.

Figure 8. Voltage changes after occurrence and fault clearance.

(a) Voltage of load bus bars

(b) Voltage of induction motor bus
Figure 9. SAP plot in stable conditions.

(B) \(P_2\) constrain: Position \(P_2\) will exist if position \(P_1\) conforms to the first condition described in Section 3. When the change path on the SAP plot reaches position \(P_2\), it compares the value \(\Delta F_i\) in this position with its value in position \(P_1\). If \(\Delta F_i(P_1) / \Delta F_i(P_2) \geq 0.5\) the algorithm gives the time to detect the steady state without checking the \(P_2\) condition in this step, and in the continuation of the check, the algorithm enters the final condition check section according to the procedure shown in Figure 6. The condition \(P_2\) is that first the \(D_i\) signal is calculated according to Equation (3):

\[
D_i(t) = \Delta P_i(t - \Delta t) - \Delta P_i(t)
\]

Under steady state conditions, the \(D_i\) signal cap is expected to decrease as the \(\Delta P_i\) values approach each other. In order to find the descending or ascending changes, using the trapezoidal rule, the \(S_i\) signal equal to the relation (4) is calculated.

\[
S_i(X) = \sum |D_i(t - \Delta t)| + \frac{D_i(t - 2\Delta t) + D_i(t)}{2}
\]

\(S_i\) signal for both steady and unstable states in states (a) and (b) is shown in Figure 5.

The 2P condition is such that if (2) \(S_i \geq S_o\), the occurrence of short-term voltage instability is predicted, otherwise the algorithm will enter the final condition.

(A) Final constrain: With the occurrence of short-term voltage instability, the frequency increases in value and slope. Will be. Therefore, the two indices \(P_i\) and \(\Delta F_i\) are monitored after position \(P_2\) until the last sample, and as soon as the algorithm detects an increase in amount \(\Delta F_i\) and a decrease in \(\Delta P_i\) for 50 consecutive samples, short-term voltage instability is predicted. Otherwise, the algorithm detects stable conditions.

An overview of the proposed algorithm is shown in Figure 6.

5. Simulation results

In this section, the performance of the algorithm for the occurrence of conditions leading to steady state and short-term unstable voltage on the 39-bus IEEE network (Tightiz et al., 2020), as shown in Figure 7, is investigated.

The required dynamic simulations are performed in Dig SILENT software, and the proposed algorithm is implemented in MATLAB software. The first system to be considered is the 39-bus standard IEEE system. This system has 3 induction motor in bus 18-21-26, 3 AVR, total synchronous and 11 times with and 259 MW, 3.81 MW. Other dynamic information of this
Figure 10. Voltage changes after occurrence and fault clearance.

(a) Load voltages

(b) Induction motor bus voltage

Figure 11. SAP plot in unstable conditions.
system is extracted from the reference (Kapeller et al., 2021). This system is shown in the figure below.

At relationships 5 and 6, 0 V and 0 f, the rated voltage and frequency are frequent. Also, in order to consider the performance of the PMU, a sampling time interval of 0.01 seconds has been selected.

5.1. Investigation of stable conditions using SAP
The performance of the proposed algorithm for the occurrence of three-phase short circuit fault on line 15-16 at a distance of 25% from line 15 for 7 cycles (116.6 ms) is investigated in this section. The load bars are shown in Figure 8 (a,b), respectively.

According to the first step of the algorithm, four G6, G4, G3 and G7 generators are selected as candidate generators and SAP panel for G6 generator the title of the generator most affected by the fault is shown in Figure 9.

According to Figure 9, none of the three constrain for finally, P1 and P2 are met, and the algorithm correctly detects stable short-term voltage conditions.

5.2. Investigation of unstable conditions using SAP
For the fault mentioned in Section A at a distance of 50% from line 15 which resulted in short-term voltage instability, the three-bus voltage with induction motor, the voltage of other load bars and the SAP plate per G6 generator, respectively, are shown in Figures 10(a-b and 11) are shown.

As shown in Figure 11, the P1 condition is confirmed by the algorithm and detects the occurrence of short-term voltage instability within 0.35 seconds after the perturbation occurs. As shown in Figure 10, this time compared to the time of collapse and short-term voltage instability, the proposed high-speed algorithm predicts the occurrence of this instability.

5.3. General review of short-term voltage stability conditions
Intended events include three-phase short-circuit faults in 5 different locations on transmission lines (at 0%, 25%, 50%, 75% and 100%) in the case of fault clearance in the standard three periods of 5, 6 and 7. The cycle is separated by a fault line from the network, so 510 modes are considered to evaluate the performance of the proposed algorithm. The performance results of the proposed algorithm under the above events are shown in Table 1.

According to the results shown in Table 1, the proposed algorithm has 100% accuracy in both steady state and short-term unstable voltage detection modes.

6. Conclusion and suggestions
In general, the common problem of estimation methods when voltage instability is their performance in the event of power fluctuations after large events in power systems. The aim of this section is to provide a method that has the ability to predict voltage instability, which can be used to determine the appropriate time to cut the voltage drop. Voltage amplitude alone is not a good criterion for determining voltage instability because it is possible for the voltage amplitude to fall below the set threshold for a moment after the event, but return to the desired level with the performance of equipment such as AVR. Numerous simulations show that when the system experiences voltage instability, in addition to the voltage amplitude decreasing slightly below the set threshold value, the changes in frequency and inertia rate also have a negative value. Therefore, in this article, in order to predict voltage instability, in addition to voltage range, frequency and inertia rate changes have also been used. Two indices of frequency deviation and inertial frequency response have been calculated online. Short-term voltage was provided. The performance of the proposed algorithm for the occurrence of three-phase short circuit error on line 15-16 at a distance of 25% from line 15 for 7 cycles (16 ms). Checked out. According to the simulation results, the proposed algorithm has 100% accuracy in predicting unstable
conditions and detecting short-term stable conditions. And as a suggestion for future work, neural networks and the Internet of Things can be used in this type of prediction, and also responsive loads can be added to the system to lead to optimal values in moments of instability.

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Acronyms

| UC      | Unit commitment                      | MCP   | Market clearing price         |
|---------|--------------------------------------|-------|-------------------------------|
| CBUC    | cost best unit commitment            | LR    | Lagrange Relaxation           |
| SCUS    | Security best unit commitment        | EP    | Evolutionary programming      |
| GENCO   | Generation company                   | EP    | Contract for different        |
| DR      | Demand response                      | DFO   | Simulated annealing           |
| TOU     | Time-of-use                          | SA    | Power                         |
| CPP     | Critical peak pricey                 | IPM   | Feasibility cut               |
| RTP     | Real time pricey                     | PX    | Optimality cut                |
| SUC     | Stochastic unit commitment           | PRA   | Payment for Reserve allocated |
| MUPt    | Minimum up-time                      | RU    | Relaxed unit                  |
| MDT     | Minimum demand time                  | GU    | Grand of uncertainty          |
| RR      | Ramp rate                            | NP    | Non-deterministic hard program|
| MRU     | Must run unit                        | FC    | National renewable energy laboratory|
| MOU     | Must out unit                        | OC    | Feasibility cut               |
| LP      | Lining program                       | NREL  | Demand-supply Balance         |
| MILP    | Mixed integer Lining program         | DSB   | Energy does not supply        |
| PBUC    | Price-Based unit commitment          | ENS   | AutoRegressive integral Moving Average|
| ARIMA   | Autoregressive integral Moving Average| SARIMA| Stationary AutoRegressive integral Moving Average|
| VB      | Decision variable                    | MNHOPO | modified self-organizing hierarchical PSO |

1 Intelligence wide-area measurement system (IWAMS)
2 Phasor Measurement System (PMU)
3 Intelligence generation bus (IGB)
4 Host computers
5 Phasor Data Concentrator (PDC)
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