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A Novel Projective Integration Method (Pim) For the Efficient Transient Stability Simulation of Power Systems with High Dg Penetration

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ABSTRACT

This essay deals a novel projective integration method (PIM) for the efficient transient stability simulation of power systems with high DG penetration. One procedure of the proposed PIM is decomposed into two stages, which adopt mixed explicit implicit integration methods to achieve both efficiency and numerical stability. Moreover, the stability of the PIM is not affected by its parameter, which is related to the step size. Based on this property, an adaptive parameter scheme is developed based on error estimation to fit the time constants of the system dynamics and further increase the simulation speed. The presented approach is several times faster than the conventional integration methods with a similar level of accuracy. The proposed method is demonstrated using test systems with DGs and virtual synchronous generators, and the performance is verified against MATLAB/Simulink

Key words: *PIM, Distribution generation, Synchronous generators, Adaptive parameters*

I. INTRODUCTION

The majority of distributed generation involving sources require inverters on the front end when connected to the grid. However, inverters do not have a rotating mass and thus have low inertia. Traditionally, the voltage and frequency stability of power grids are mainly supported by conventional rotating synchronous generators with large inertia coupled with a high short-circuit current ratio (SCR). Thus, the gradual subsituation of synchronous generators by the inverter-based distributed generators (DGs) may result in poor transient responses of power systems during large disturbances. If these issues are not well addressed, the poor responses may develop into a transient stability problem . To address this simulation, the concept of virtual inertia has been developed to im-prove the stability of power systems , wherein the "virtual synchronous generator" (VSG) is the most popular one. The VSG concept provides new control strategies for controllable DGs, such as batteries, to make them behave similar to a synchronous generator

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and provide virtual inertia to power grids. Thus, the integration of DGs and VSGs can affect the dynamic behavior of the power system as a whole. Time-domain simulation is the most accurate and reliable approach to evaluate the dynamic behavior of power systems. However, the computational efficiency of such simulations is severely limited by the multi-time-scale property of power systems. The multiple time scales of conventional power systems mainly come from the different dynamics of synchronous generators and their regulators.

This project presents a projective integration method (PIM) for the fast transient stability simulation of power systems with high DG penetration. The main motivation is to take the ad-vantages of both explicit and implicit methods: efficiency and numerical stability. One procedure of the PIM consists of two stages. First, several steps of integration are performed using explicit methods with a small step size corresponding to the time constants of the fast components of the simulated system. Then, based on the previous results, a projective integration step with a larger step size is performed using an implicit pre-diction-correction method. The concept of the projective method was first proposed by Gear for stiff problems with gaps in their eigen value spectrum [29], and an extrapolation method, which had been proved equivalent to the explicit Euler method, was adopted in the projective stage. This scheme has been widely used for multi-time-scale simulations in the chemical, thermodynamic and molecular physical sectors. However, the numerical stability of Gear's projective method can be easily influenced by the step size, and thus, it is difficult to improve the computational efficiency further. The PIM proposed here adopts the implicit prediction-correction method for the projective integration, and the former extrapolation method is used as one component of the predictor. Through this modification, the numerical stability of the proposed PIM is no longer affected by its parameter related to the step size. In addition, other properties of the PIM and the contributions of the present paper are summarized as follows:

1) The small-step integration in the PIM is adopted to reflect the fast dynamics of the inverter-based DGs.

2) The projective stage in the PIM is performed to reflect the slow dynamics and overall trends of the fast dynamics of the simulated system.

3) The PIM has an accuracy of order 2.

4) This paper also proposes an adaptive parameter control scheme for the PIM based on error estimation. The error estimation is convenient to realize through the explicit integration steps of the PIM, and the step sizes of the projective integration can be controlled to fit the dynamics of the simulated system adaptively.

of the proposed PIM, which has not been discussed before in the literature.

6) The proposed PIM is demonstrated on two test systems with DGs and VSGs.

II. MODELLING OF VIRTUAL SYNCHRONOUS GENERATOR

The basic concept of a VSG is shown in Fig. 1. In common practice, energy storage devices, such as batteries, are connected to the DC side of the VSG inverter.

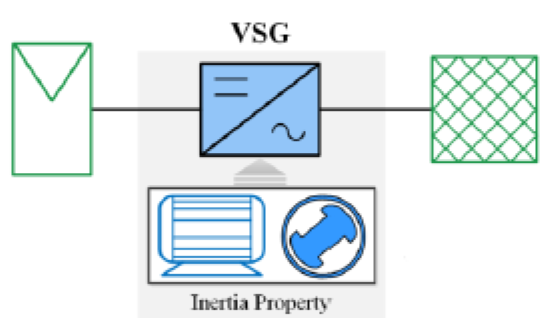

Fig. 1. Basic concept of a VSG.

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A. Swing Equation for VSG Inertia Emulation

The main purpose of a VSG is to emulate the inertia and damping properties of electromechanical synchronous gener-ators. These two main aspects can be captured by the swing equation (1), which is widely used in the literature on power system stability and dynamics

$$J\frac{d\omega_g}{dt} = T_m - T_e - D(\omega_g - \omega_0) \qquad (1)$$

where J represents the moment of inertia, D is the coefficient of fiction loss of the synchronous generator, ω_g and ω_0 denote the angular and synchronous speed of the generator, respectively, T_m is the mechanical torque produced by the prime motor, and T_e is the electrical torque.

B. Control Strategy of a VSG

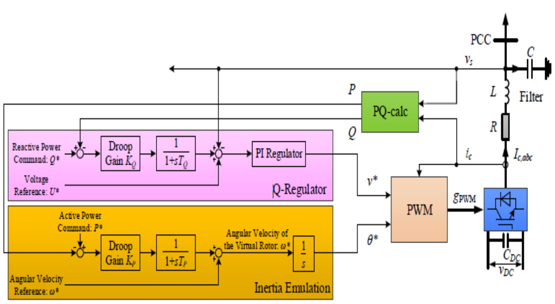

Fig. 2. Control scheme of the VSGs for transient stability analysis.

As shown in Fig. 2, the mechanical component of a synchronous generator is emulated by the VSG controller as a logical concept, which is electrically fully effective from a grid perspective. The damping gain KD of the emulated synchronous generator is inversely linked to the droop gain KP. Moreover, the time constant TP of the low-pass filter on the active power flow serves as an analogous function of the virtual inertia, which has a significant impact on the time scale of the system. Furthermore, the parameters selected for VSG implementations are not constrained by the physical design of any real synchronous generator. Thus, the diversity of the parameter selection of VSGs may aggravate the stiffness of the transient stability problem.

$$\begin{cases} \frac{dx}{dt} = f(x, y) \\ 0 = g(x, y) \end{cases} \qquad (3)$$

III. PROJECTIVE INTEGRATION METHOD

In the pro-posed PIM, one procedure consists of several explicit steps with a small step size, followed by a projective step with a large step size using an implicit prediction-correction approach. We call the small step integration the inner integrator, whereas the large projective step is referred to as the outer integrator. To fairly compare the computational efficiency of the PIM with the commercial simulator DIgSILENT Power Factory, the current-injection form of the algebraic equations is adopted during the inner and outer integration for the consistency of models. The algebraic equations are nonlinear since distribution generation is considered during the simulation. Accordingly, we use the Newton Raphson (NR) method to solve the nonlinear algebraic equations, which is the same as that of Power Factory.

Specifically, one procedure of the PIM integrates from time t_n to t_{n+k+M} as follows:

Stage I: A suitable explicit integration method is used for k steps with a small step size Δt

corresponding to the fast time constants of the simulated system. Thus, the state variables $\boldsymbol{x}_{n+k}$ at t_{n+k} can be computed. The explicit integration method must have at least second-order accuracy (the reason will be given later).

Stage II: Firstly in this stage, needs to be implicitly differenced at t_{n+k+M} as

$$\begin{cases} \boldsymbol{x}_{n+k+M} = \boldsymbol{x}_{n+k} + \frac{1}{2}\Delta T[\boldsymbol{f}(\boldsymbol{x}_{n+k}, \boldsymbol{y}_{n+k}) + \boldsymbol{f}(\boldsymbol{x}_{n+k+M}, \boldsymbol{y}_{n+k+M})] \\ \boldsymbol{g}(\boldsymbol{x}_{n+k+M}, \boldsymbol{y}_{n+k+M}) = 0 \end{cases}$$

where $\boldsymbol{x}_{n+k+M}$ denotes the system state variables at t_{n+k+M} , $\boldsymbol{y}_{n+k}$ and $\boldsymbol{y}_{n+k+M}$ refer to the algebraic variables at t_{n+k} and t_{n+k+M}, respectively. Then, $\boldsymbol{x}_{n+k+M}$ and $\boldsymbol{y}_{n+k+M}$ are computed with a large step size of $\Delta T = M\Delta t$ (M is a positive integer) in the following manner:

a) The differential equations of (3) are integrated from t_{n+k} to t_{n+k+M} by the explicit Euler method to predict the initial estimates of $xn+k+M$ as

$$\boldsymbol{x}^*_{n+k+M} = \boldsymbol{x}_{n+k} + \Delta T \boldsymbol{f}(\boldsymbol{x}_{n+k}, \boldsymbol{y}_{n+k})$$

and compute the algebraic function $\boldsymbol{g}(\boldsymbol{x}^*_{n+k+M}$, $\boldsymbol{y}^*_{n+k+M}$) = 0 to predict the initial estimates of $\boldsymbol{y}_{n+k+M}$.

b) Correct $\boldsymbol{x}^*_{n+k+}$ and compute the initial estimates of $\boldsymbol{x}_{n+k+M}$ through

$$\boldsymbol{x}^{(0)}_{n+k+M} = \boldsymbol{x}_{n+k} + \frac{1}{2}\Delta T[\boldsymbol{f}(\boldsymbol{x}_{n+k}, \boldsymbol{y}_{n+k}) + \boldsymbol{f}(\boldsymbol{x}^*_{n+k+M}, \boldsymbol{y}^*_{n+k+M})]$$

and then the initial estimates of $\boldsymbol{y}_{n+k+M}$ can be computed by solving $\boldsymbol{g}(\boldsymbol{x}^{(0)}{}_{n+k+M}$, $\boldsymbol{y}^{(0)}{}_{n+k+M}$) = 0.

c) Further correct $^{(0)}{}_{n+k+M}$ based on

$$\boldsymbol{x}^{(1)}_{n+k+M} = \boldsymbol{x}_{n+k} + \frac{1}{2}\Delta T[\boldsymbol{f}(\boldsymbol{x}_{n+k}, \boldsymbol{y}_{n+k}) + \boldsymbol{f}(\boldsymbol{x}^{(0)}_{n+k+M}, \boldsymbol{y}^{(0)}_{n+k+M})]$$

and then compute $\boldsymbol{g}(\boldsymbol{x}^{(1)}{}_{n+k+M}$, $\boldsymbol{y}^{(1)}{}_{n+k+M}$ (1)) = 0 to correct $\boldsymbol{y}^{(0)}{}_{n+k+M}$.

d) Terminate the iterations when the convergence condition is satisfied. If not, one can substitute $\boldsymbol{x}^{(1)}{}_{n+k+M}$ and $\boldsymbol{y}^{(1)}{}_{n+k+M}$ for $\boldsymbol{x}^{(0)}{}_{n+k+M}$ and $\boldsymbol{y}^{(0)}{}_{n+k+M}$ in (respectively, and then repeat c) and d) until the iterations converge.

$$\left\|\boldsymbol{x}^{(1)}_{n+k+M} - \boldsymbol{x}^{(0)}_{n+k+M}\right\| < \xi.$$

In (8), ξ denotes the error threshold.

In the procedure above, the parameters k and M represent the number of inner integration steps and the multiple of the step size Δt during the outer integration, respectively. Assum-ing that k = 3 and M = 5, the schematic diagram of one pro-cedure of the PIM is shown in Fig. 3.

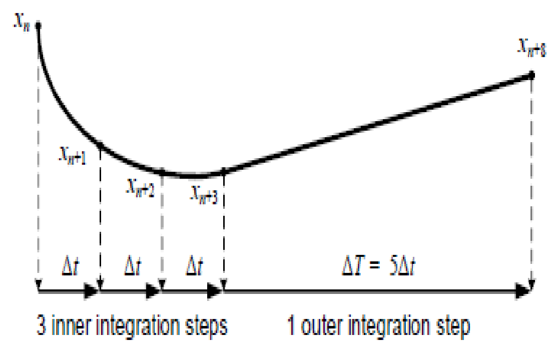

Fig. 3. Schematic diagram of one procedure of the PIM.

IV. ADAPTIVE PARAMETER CONTROL FOR THE PIM

Stability domains of the conventional integration algorithms with A-stability, such as the trapezoidal method, are not affected by their step sizes. Thus, some variable step size meth-ods can be adopted for these algorithms to accelerate the calculation speed regardless of stability. Similarly, the stability domain of the PIM is irrelevant to its parameter M, and accordingly, we propose an error estimation method and an adaptive parameter control scheme for the PIM in this section

A. Error Estimation for the PIM

The error estimation for the PIM needs to be discussed sep-arately for different orders of its inner integration method:

1) Second-Order Integration Method:

We assume that the modified Euler (ME) method is selected as the inner integrator of the PIM. The third-order term in the Taylor expansion of the ME method from time $n\Delta t$ to $(n + a)\Delta t$ can be described as

$$\eta_{\text{Inner}} = \frac{1}{6}(a-1)a(a+1)\Delta t^3 \frac{d^3 x_n}{dt^3}.$$

Then, given parameter k, the third-order term in the Taylor expansion of the PIM proceeding one overall integration step with parameter M is obtained as

$$\eta_{\text{PIM}}(M) = \left[\frac{k(k-1)(k+1)}{6} + \frac{k^2}{2}M + \frac{k}{2}M^2 + \frac{1}{4}M^3\right]\Delta t^3 \frac{d^3 x_n}{dt^3}$$

and thus the LTE of the PIM can be approximated by neglecting the high-order residuals as

$$T(M) = \frac{1}{12}(2k - M^3)\Delta t^3 \frac{d^3 x_n}{dt^3} + O(\Delta t^4) \approx \frac{1}{12}(2k - M^3)\Delta t^3 \frac{d^3 x_n}{dt^3}$$

2) Integration Method of Order p ($p > 2$): In this case

$$\eta_{\text{Inner}} = \frac{1}{3!}(a\Delta t)^3 \frac{d^3 x_n}{dt^3}$$

and further, the LTE can be estimated as in a similar way.

$$T(M) = -\frac{1}{12}M^3\Delta t^3 \frac{d^3 x_n}{dt^3}.$$

The differential term can be estimated by the Lagrange interpolation formula as

$$\frac{d^3 x_n}{dt^3} \approx -\frac{1}{\Delta t^3}(x_n - 3x_{n+1} + 3x_{n+2} - x_{n+3}).$$

It is worth noting that the parameter k of the PIM should be no less than 3 to ensure the solvability

B. Adaptive Parameter Control Strategy

The main concept of the PIM with adaptive parameter control (PIM-AP) is as follows. First, after the inner integration of the l_{th} step, the parameter M_l of the upcoming outer integrator is obtained by a priori error estimation based on M_{l-1}, namely, the parameter of the last step of the PIM-AP. Then, we proceed with the first three stages of the outer integrator using M_l and estimate the local error of the lth step through a posteriori error estimation. If the local error satisfies the error condition, M_l is accepted and the rest of the stages will be performed. Otherwise, Ml is rejected and the outer integrator will be recalculated with an updated parameter. The pseudo code for the adaptive parameter control of the PIM is provided in Algorithm 1. In Line 7 of Algorithm 1, $\lfloor x \rfloor$ represents the "floor" function, taking the integer part of x and ignoring the decimal part, and τ in Line 10 denotes the estimated error tolerance.

V. SIMULATION RESULTS

The simulation time is set to 5 seconds, and the active power reference P* of the VSG unit is changed from 0 to 0.1, in per unit, at 1.0 s under the condition that the reactive power is 0. In this scenario, the active power step response of the VSG is featured, and the PIM-AP is verified by the electromagnetic simulator MATLAB/Simulink with the ode23 solver. The maximum value of the parameter M of the PIM-AP is set to 40, and the simulation results are shown in Fig. 4. The results of the PIM-AP are highly similar to those of Simulink.

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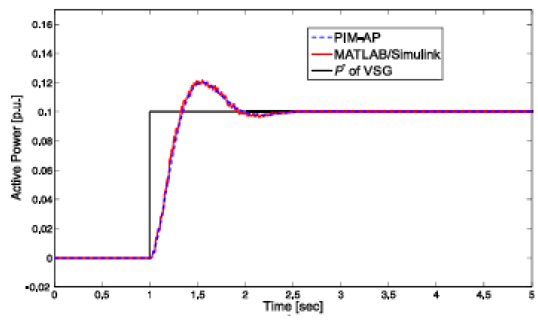

Fig 4.(a)Simulation results when P* of the VSG unit changes

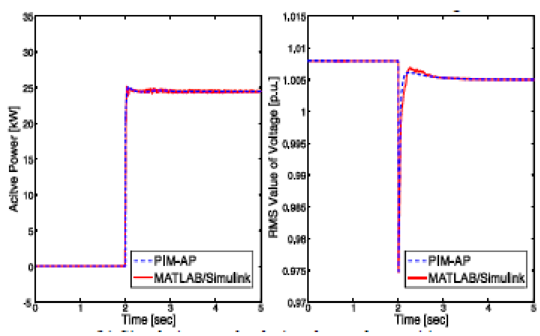

Fig 4.(b) Simulation results during the mode transition

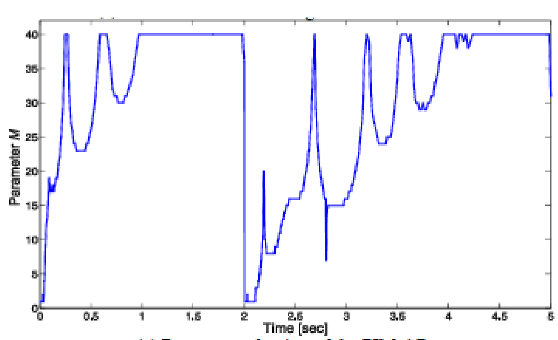

Fig 4.(c) Parameter adaption of the PIM-AP

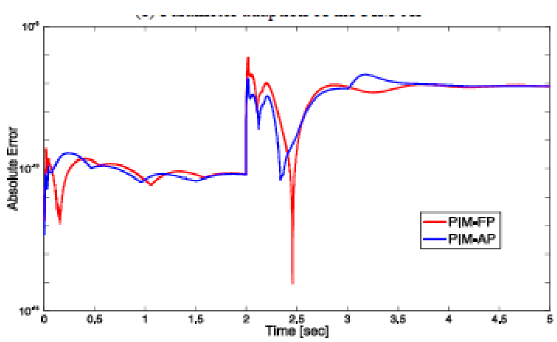

Fig 4.(d) Absolute errors of the PIM-AP and the PIM-FP with k = 3 and M = 8

The PIM-AP is verified by the commercial transient stability simulator DIgSILENT Power Factory in this case. The simulation results are shown in Fig. 5, which indicates that the results of the PIM-AP and Power Factory are indistinguishable. The VSG units respond rapidly and reduce the impact of large disturbances on the integrated system.

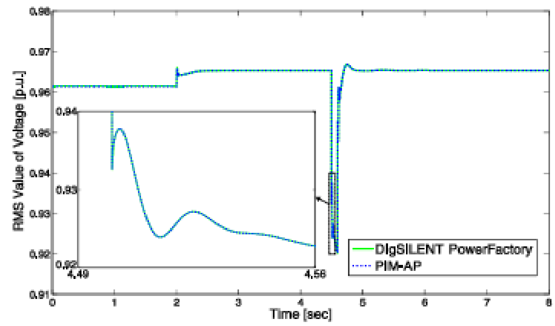

Fig 5.(a) Simulation results of the PIM-AP and DIgSILENT Power Factory RMS values of the voltage of node 60

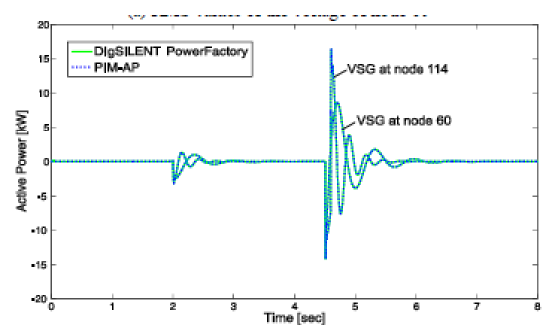

Fig 5.(b) Simulation results of the PIM-AP and DIgSILENT Power Factory Active power outputs of the VSG units

VI. CONCLUSION

The proposed PIM decomposes one procedure into several small steps corresponding to the time constants of the fast dynamics and one projective step for accelerating the simulation speed, which are treated separately with different methods. The PIM is a second-order method, and its numerical stability is not affected by the selection of the step size. Based on this property, we have also presented an adaptive parameter control strategy for the PIM to further improve its computational performance. Various simulation experiments were performed on test systems with DGs and VSGs, and the accuracy of the PIM was verified against that of electromagnetic simulation using the MATLAB/Simulink tool.

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