Aspects of stability issues of HVAC/HVDC coupled grids

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Keywords

«Stability analysis», «Multi-terminal HVDC», «optimization», «AC-DC».

Abstract

This paper explores MTDC control expectations and attempts to investigate the challenges preventing usage of MTDC grid to enhance power system stability. Protection and dispatching are not in the scope of this paper. Dynamic performance up to tens of seconds is only considered (AC voltage regulation is therefore not studied here).

Introduction

Power system network is undergoing structural changes mainly driven by the increase of share of renewable energies [1] implying more power electronic (PE) interfaced grids. These changes create challenges for the TSOs to operate the system. To solve this issue, reinforcement and/or upgrading of the grid is one solution and development and expansion of High-Voltage Direct Current (HVDC) [2] has proven to be the most adapted upgrading solution in many situations. A more complex configuration of power transmission through DC lines is called MTDC implicating multiple terminals of conversion and therefore a more elaborated system compared to point-to-point HVDC. Since renewable power production devices are replacing classical machines, their intermittence decreases reliability of primary reserves of power system. Another problem emerges directly from the use of PEs: the inertia classically provided to the system by AC generators is not equivalently provided directly by power converters interfacing electrical production [3]. While PE devices allow faster and more flexible power control for stability enhancement [4], their vulnerability against perturbations makes power system less robust.

The increasing integration of HVDC in the current grid, will lead to complex interconnected AC/DC grids. Controllability of HVDCs could serve in stabilizing the system [5] such as in power flow balancing and participation to frequency services to HVAC side [6]. MTDC grid can contribute to power balancing of connected AC grid by charging or discharging DC grid capacitances. However, if no power storage or fast production systems are connected to the system, the DC power needed power should come from/go to another AC system, causing its imbalance. The increasing amount of HVDC, together with the use of supplementary controllers leads to interactions – between initially decoupled AC systems connected through DC lines or between AC and DC systems too – that affect global AC/DC power system stability due to coupling between the modes of both grids. For this reason, MTDC grid control must be optimized: what terminal to take the power from? What amount of power to take from each terminal? Interoperability questions emerge too (feasibility, coordination, automation of actions, etc).

This paper examines the literature of AC & DC power system stability solutions especially looking at how DC system can help enhance AC stability. The paper first investigates the DC grid stability requirements and challenges that may affect it as well as proposed solutions. It looks then for existing solutions to enhance AC stability and checks their limits. Note that AC power system controllers will not be explored but instead the possibilities offered by HVDC links will be specially studied. This paper does not attempt to survey all supplementary controllers that can be added to enhance AC & DC stability but focuses on main ones to move to expectations from these controllers in case of MTDC grid. It also studies some difficulties that could prevent MTDC direct replacement of HVDCs and proposes first steps for AC & DC power system stability enhancement through optimal usage of MTDC grid.

This paper is organized as follows. Section II summarizes offered possibilities for AC stability enhancement through HVDC supplementary controllers. Section III explores the requirements and challenges in DC grid. Section IV reviews opportunities offered by MTDC grid control to enhance AC & DC stability and the difficulties to implement the control. Section V concludes the paper.

I. AC grid stability

a. Requirements for AC stability

TSOs require from the classical AC system to be 'N-1 criterion'-compliant meaning that control should withstand loss of one component (line, generation unit, etc) in an initial grid operating with N components.
AC grid stability is classically divided into three main aspects [7] [8]:

- Rotor angle: transient able to split system or small disturbance creating power oscillations,
- Frequency: short term or long term,
- Voltage: large or small disturbance.

b. HVDC control to meet requirements of AC stability

When HVDC system interfaces AC system, these stability aspects can be deteriorated or even jeopardized if no proper control is implemented and, on the opposite, enhanced in case of appropriate control. In contrast, oscillating modes may be excited and wide AC grid oscillations may occur when improper HVDC power control is applied. In [9], power reference of converters needed to be manually reduced to help damp power oscillations. Finally in the case of system split incident in January 2021 (Continental Europe Synchronous Area), one recommendation in the final report was to seek better frequency support through HVDC links [10]. Thus, the question of HVDC system control arises directly.

Since power converters used to interface AC and DC grids are high-speed components that help also integrate remote renewable energy sources, better flexibility, and controllability in dynamic hosting of AC systems can be reached. In this context of new AC/DC system, HVDC part of the system is required not only to allow for power transfer but to assist AC grid in stability conservation or enhancement. The current situation is a proliferation of VSC power converters throughout the global power system, and the same is expected for future developments of the grid allowing thereby for better control of HVDC power flows. However, the impact of power electronic devices on AC system may not only be positive for stability since bad interactions may occur as it has been already observed and analyzed.

As shown in [5], some functionalities are expected from HVDC operating as either embedded or non-embedded lines in AC power systems, all of them feasible with VSCs:

- AC Voltage control
- Sub-synchronous damping
- Frequency control (Frequency Containment Reserve delivery)
- Emergency Power Control
- Power Oscillation Damping
- AC line emulation

- Synthetic Inertia

If first two controls do not influence others directly (reactive power in action), the remaining ones can even cancel themselves if not properly implemented [5] [11].
To enhance AC/DC stability, some degrees of freedom using HVDC grid through its power converters are to:

- Add controllers for power reference of converters,
- Dynamically adjust the gains of the controllers,
- Or to recalculate more convenient setpoints as converter inputs after solving for optimal power flow.

Other possibilities include modification of AC grid topology or update design requirements (line capacity limits, power converters nominal power). The focus here will be on first three approaches.
In the following, a non-exhaustive list of potential controllers will be presented as they will be reused in the last part of this paper. For each controller, many technologies exist, each having its own advantages and drawbacks despite being innovative. A zoom is made on two approaches for rotor angle stability enhancement.

- Power Oscillation Damping

Table 1: Proposed key points for POD control. These can be extended to all HVDC-based controls which will be dealt with in the following sections.

Control strategy	Observability	Data acquisition	Actuators
• Power System Stabilizer • Power Oscillation Damper (local & remote inputs) • Load shedding (load side) & bang-bang type (converter side) controls • Operating Point Adjustment • Model Predictive Control	• Signals that contain most significant information (check section IV)	• Measurements • Ttransmission system • Time delays • Processing time	• Synchronous generators • HVDC interfaced converters (LCC vs VSC)

In this section, discussion is focused on some parts of control strategy and data acquisition of Table 1. Data acquisition part may be common for all controls presented in the following sections.

Before implementing Power Oscillation Damper (POD), the PSS was a decentralized method allowing for independent power oscillation damping action for each generator. New designs such as PSS4B and adaptive tuning of PSS can play a significant role in small-signal interarea mode damping [12], [13]. However, PSS requires tuning of 6 parameters (1 gain and 5 time constants) and a centralized POD can also play a supplementary role for a given power system's optimal operation. Figure 2 in article [14] shows that remote signal used to ensure power oscillation damping can outperform local signals but delay margins limit their performance. However, only time delays' effects were studied in the article while remote signals imply using of wide-area measurement systems and availability and robustness of signal against noise were not treated in the study. Two other important points to evaluate when adding a POD are the placement of the actuator and parameter tuning.

POD controllers are widely studied today, and the emergence of machine learning and artificial intelligence allows for new ways at tuning their parameters. Figures 6.12 to 6.18 in [15] compare different machine learning-based algorithms that predict eigenvalues and classify them to the true eigenvalues of the IEEE 14-bus power system. Promising results are shown but more investigation is needed for real-time real-life application of the deep-learning-based power oscillation damping. To what extent the predictions provided are robust against system noises since a trade-off must be found between processing time and accuracy? The 'intelligent POD' (iPOD) then 'multi-band iPOD' (MiPOD) shown in [16], [17] is one of the possible improvements proposed for intelligent tuning of POD but its comparison with conventional PSSs showed that in certain circumstances the latter can have better results. It is true that, compared to conventional PSS, the 'MiPOD' needs to tune only 1 parameter per oscillation band and assures selective and adaptive damping as well, but it assumes a control dependent on wide-area measurements (availability and[18] reliability [18], transmission, processing [19]) and communication delays.

Finally, complementary action to POD control (added in the system to increase the damping of the modes at the same operating points via usage of supplementary controllers) are bang-bang type control [20], Operating Point Adjustment (OPA) [21] and Model Predictive Control that takes also the dynamics of the system into consideration instead of just performing optimal power flow. This moves the system to a new condition to have better damping of critical modes. In case of OPA for instance, POD can be the first action implemented against disturbances, while OPA can be the longer-term action to improve system's small signal stability. Moreover, OPA can be applied before the occurrence of a disturbance, providing therefore additional stability margins. Coordination between POD and OPA may be needed, too.

- Angle Difference Controller (ADC): AC line emulation

To enhance transient stability, one possibility is to emulate AC lines through VSC-HVDC control. Although this simple measure is normally done for better steady state of the AC system (powerflow concerns), it can also enhance dynamic behavior of the power system.
The injection of synchronizing power (not only damping power) by POD through DC lines to support AC grid in case of three-phase fault was investigated [22] in addition to the main topic of transient stability enhancement.

Although ADC controller is a simple controller, particular attention is needed on filtering time constant of ADC which may impact transient stability negatively as was learnt in the case of INELFE DC interconnection [23] [24]. Extremely quick or slow time constants of ADC are considered to enhance transient stability while other values can jeopardize system stability. Since ADCs are mostly used for steady state concerns, choosing a slow time constant is the best option to avoid transient instability.

II. DC grid stability

a. Requirements for DC stability

In [25], DC power system stability was explored through multiple case studies at converter's level and this affects stability of whole DC system – which affects AC & DC stability. A study of DC power system stability was done in [26] for distribution systems. If stability is only considered through checking range of operation of DC components' variables at steady state in the article, it is however important to check the paths the DC voltage and powers follow to move from one operating point to the steady state equilibrium point. Should an HVDC power system be considered stable if at some point of the operation the system deviates 'significantly' from nominal values before moving to acceptable equilibrium point at steady state? Moreover, stability margins are not the same for a DC power system where converters are saturated compared to a system operating at lower power stress. The problem is more eminent when converter ratings (voltage, power, etc) are violated. Therefore, a DC power system may be considered stable if the whole trajectory including first one operating point till a steady state is reached is acceptable (within tolerated range) and allows for higher stress. Otherwise, the equilibrium point, if one is reached, may be considered critical or unstable.

As a basis for operation, the availability and reliability of HVDC systems depend on its topology and the used components. Requirements for individual components should normally be specified during planning of the HVDC grid. For DC system stability, the main variable that should be monitored in DC operation is the DC voltage. However, the current regulations available in [27] are general requirements that need to be "specified" by TSOs at each time specific network codes are needed for AC/DC interface. Therefore, to preserve DC voltage stability, some voltage profiles have been proposed as in figure 9 in [28] [29] to show to what extent DC voltage protections should stay untriggered but AC & DC interactions should be considered too to keep discrimination between AC & DC protections and avoid unvoluntary triggering of DC protections. Thus, conclusions for range of operation of DC voltage are not straightforward as coupling with AC side needs more examination and regulatory specifications are still missing.

b. Challenges

Sudden loss of power converter is one of the main events that may jeopardize DC grid operation. This can be expressed as instant active power loss of injection or extraction and EU legislation has already taken into consideration this case [27]. Nonetheless, network code does not express direct guidelines and methodologies for calculation of the maximum allowable active power loss and it is left for TSOs to define and apply them.
While the impact on AC grid stability can be limited by this value, what about the impact on DC grid stability in case of MTDC system? Sudden loss of power converter can be much more impactful on DC side than on AC side, so what are needed controls to preserve DC stability in such case?

III. Expectations from MTDC grid for AC/DC stability enhancement

a. From point-to-point HVDC to MTDC

- Transposition of some types of controls is not straightforward

To maintain stability of DC grids, many DC Voltage control methods exist [30]. DC Voltage control exists for point-to-point (PtP) HVDC where one converter regulates DC voltage while the other controls power flow. However, connecting an AC grid to a Multi-Terminal DC system is not as simple as connecting it to a PtP HVDC due to added complexity. Paradoxically, when a power converter is down in a PtP HVDC, all the DC link gets down, but MTDC grid should allow for maintained operability even with one converter down making it a better solution than cascaded PtP HVDCs.
Extension of DC voltage control from PtP to MTDC is possible through 'master-slave control mode' where one terminal plays the role of slack bus to control DC voltage by absorbing any power flow variation in DC grid while the remaining terminals control power flow. This strategy has however its own drawbacks since all balancing power responsibility lies on one converter and system (at least DC system) depends entirely on one component which fails to meet N-1 contingency criterion.
To cope with this issue, 'voltage-margin control mode' was invented where terminals operate in constant power control mode until certain voltage range is violated (maximal power reached for converter in master mode) where they switch to constant voltage control mode. In this strategy, it is true that system does not rely on one converter for power flow and voltage control in disturbed situation, but it relies on it for steady-state operation and large efforts of power balance still rely on one component to a certain extent. Moreover, when power control mode switches, big power disturbances may occur, and AC grid may be destabilized.
For these reasons, distributed voltage control is needed for MTDC: 'DC voltage droop control' [31] implicates more than one terminal in DC voltage and active power regulation.
The DC Voltage droop control formula that will be used later in the paper is:

$$P_{hvdc_{ref}} = K_{dc_{droop}} * (V_{dc_{meas}} - V_{dc_{base}})$$

- One control action can affect more than only targeted stability aspect

In MTDC grid, since multiple converters are involved, it is expected to benefit from the available power headroom of each one of them to add a control that helps AC system stability. However, implementing these controls must not be as straightforward as in PtP HVDC where effects are directly expected.

For instance, in 'master-slave' configuration in HVDC, frequency droop should be implemented in converter in 'slave' mode since no power reference can be changed in converter in 'master' mode responsible of DC voltage regulation. Effect of frequency droop and DC voltage controls are known in advance. When transposed to MTDC, since DC voltage droop control mode is implemented instead of 'master-slave' mode, all converters in this control mode are expected to have their power references changed according to the needed voltage control efforts for DC side. Frequency droop, in parallel, is expected to modify the power reference of given converters too according to the needed frequency control efforts for AC side. These two control efforts, normally destined to target separate stability aspects (DC voltage by DC voltage droop control & AC frequency by frequency droop control), will then interact [11] and affect each other in a way that may have better effects if the control actions are coordinated, if power injections and extractions are calculated by a higher-level controller.
Therefore, need for global stability assessment and enhancement appears evident with hybrid AC/DC systems, and it gets even more important when complexity of MTDC systems is involved to be able to benefit from the flexibility expected from MTDC.

b. Global AC/DC system stability enhancement

i. Necessity of assessment for prioritization of stability aspects afterwards

Before applying control to AC/DC system, assessment should be performed to have a clear vision of what stability aspect needs to be enhanced and in which priority. This means that a certain 'score' should be given to the system depending on each stability aspect state.

- How should the 'score' be established?

To do so, TSOs need indicators that reflect the power system's stability state for each aspect of stability. For a given stability aspect 'lambda', proper indicators should be defined to help evaluate margins of stability and conclude whether the system is lambda-stable or not. These indicators will help control in allocating power according to the assessed 'need' for stability enhancement. The Key Performance Indicators chosen to calculate stability score are in their turn based on measurements coming from system PMUs. To give best assessment possible, observability study may be conducted to determine which measurements can best detect stability issues in the system. For instance, observability study helps choose the measurements that theoretically contain and illustrate best among available data for oscillating mode detection [32].

ii. Coordination of control actions

- A 'global' score of the hybrid AC/DC system

The score discussed above for each stability aspect should be combined with another stability aspect's score so that priority can be established in stability enhancement efforts. For this reason, a global stability function needs to be calculated with dynamic weighting of each stability aspect's indicators to put priority on most endangered stability aspect for enhancement.

- Should all controls be always activated? What compromise is needed between control actions?

Optimal placement of controllers can be a matter of fact due to added costs of each implemented control action. For this reason, placement of controllers or at least their activation must guarantee they maximally impact power stability for improvement, otherwise all power efforts are lost. Study may be conducted to determine what injection point of power control will theoretically have this highest impact. Since control effects are not just linear superposition of effects for each stability aspect, a compromise should be found so that control effects are the best for 'global' stability enhancement. With all degrees of maneuver offered by MTDC system (flexibility & maneuverability of power flows, additional control possibilities, effort mutualization for AC system stability enhancement, etc), control coordination becomes more prominent. Though an optimization approach requires important calculation efforts, it guarantees the system has best control actions to enhance global stability.

- 'Global stability' case study

To evaluate the 'global' stability aspect of the system, the following benchmark (Fig.1) was simulated on Modelica-based environment. AC grids were tested alone then tested MTDC grid was added to connect AC zones 1 & 2. Generator units are equipped with speed governors. Initial power flow (table 2) is performed to quickly reach steady state power curves before applying positive active power step at upper VSC. Before any disturbance, the power converters' references are put to 0 and no power was flowing from/to AC side through them. Following case studies are performed to show effects of frequency droop control applied through VSC3 on non-targeted stability aspects: DC voltage of MTDC system and rotor angle of AC zone 2 (small-signal stability).

Table 2: Power flow initialization of benchmark's generators and loads. Power converters deliver zero power output at initial system operation.

Component	Initial Active Power Flow (MW)	Component	Initial Active Power Flow (MW)
Generator G1	500	Load L1	1027
Generator G2	527	Load L2	300
Generator G3	500	Load L3	700
Generator G4	500		

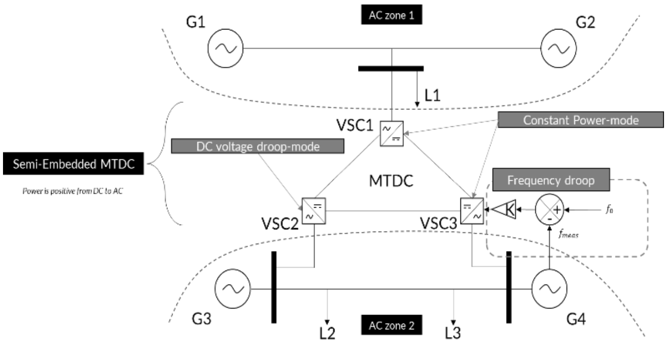

Figure 1: Used benchmark for AC & DC stability study.

- First case study: interaction between frequency droop and DC voltage droop controls affecting DC voltage stability. A step of P_{VSC1} asked by AC Zone 1 (could be load change, compensation of generator/line tripping, etc.)

In this case study, DC voltage drop for same DC Voltage droop gain at VSC2 (8MW/kV) was observed with different values of frequency droop gains through sweeping this parameter and running multiple simulations. The following results were observed:

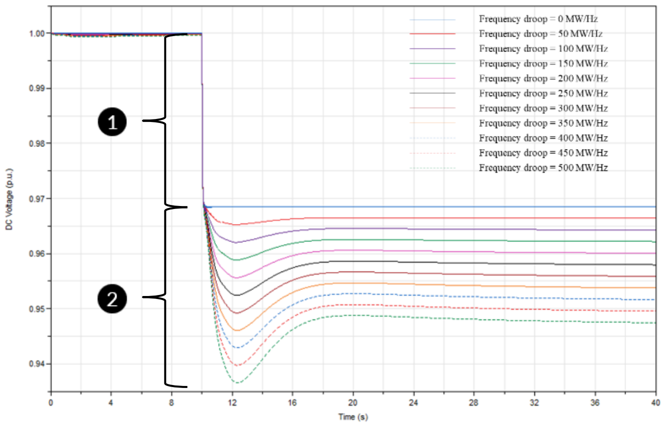

Figure 2: DC voltage profiles for different frequency droop gains. Single effect of DC voltage droop control and its combined effect with frequency droop control is shown.

❶ DC voltage drop due to single effect of DC voltage droop control. For 100 MW step, final DC voltage value is calculated as the following:

$$V_{dc_{final}} = V_{base_{dc}} - \frac{P_{step_{VSC1}}}{K_{dc_{droop}}}$$

$$V_{dc_{final}} = 387500\, V$$

$$V_{dc_{final}} = 0.96875\, p.u.$$

❷ Frequency droop control degrades DC voltage's transient and final values. Increased voltage drop comes with increased value of frequency droop controller gains.

However, as was mentioned before, global stability evaluation is needed before concluding on the usefulness of a proposed control (frequency droop in this case). Therefore, rotor angle stability was studied in a second approach.

- Second case study: effect of frequency droop on rotor angle stability. A step of P_{VSC1} asked by AC Zone 1 (load change, compensation of generator/line tripping, etc.)

In this case study, curves for different values of the step at VSC1 are compared to emphasize the effect of the single presence/absence of frequency droop control at VSC3. The following results were obtained by simulation:

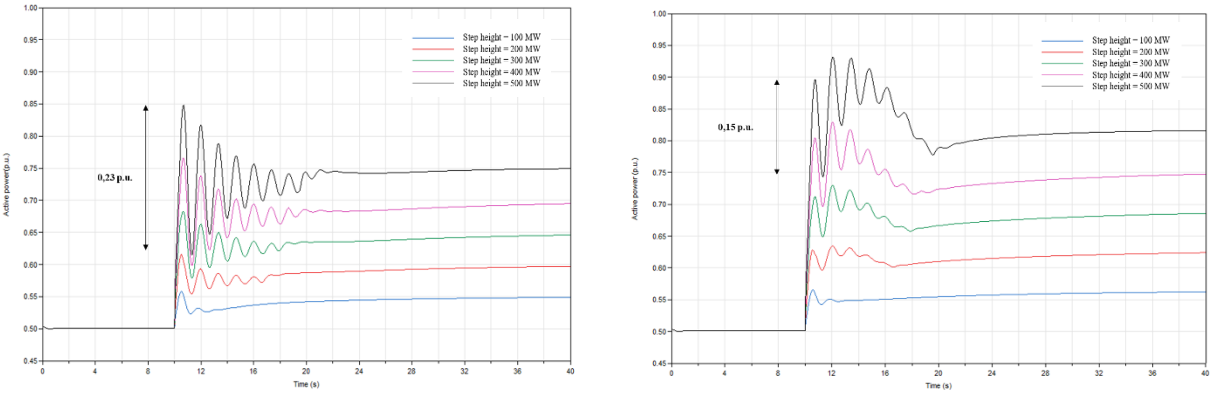

Figure 3: Power oscillations observed at AC line connecting L3 to bus connecting VSC3 and G4 for different step heights.
Left side: frequency droop is deactivated (gain = 0). Right side: frequency droop gain = 100 MW/Hz.

Frequency droop control affects positively power oscillations in this case since first swing is smaller when frequency droop gain is bigger (for highest power step at VSC1, first swing oscillation values are shown in Fig. 3). This reflects better rotor angle stability in AC system zone 2.
The equation for frequency droop controller output is:

$$P_{hvdc_{ref}} = K_{f_{droop}} * (f_{meas} - f_n).$$

As this mathematical expression suggests, frequency droop first detects difference between the nominal frequency and the measured one. Due to added power stress in AC zone 2, power starts to oscillate due to excited modes. As known, frequency acts similarly as the oscillating active power in the AC zone. Therefore, due to relatively large time reaction of generator turbine governors and the relatively small structural damping, speed of generators tends to increase with positive power oscillation and to decrease with negative oscillation. This explains measurable frequency oscillations at G4.
In this logic, as previous equation shows, frequency droop measures these oscillations in f_{meas} and tends to reduce the difference between oscillating frequency and fixed nominal frequency which leads to damping of power oscillations like what would PODs do. The damping is more eminent compared to case without frequency droop because VSC3's power injections act very fast and damping is not due to turbine governors and generator's damping in this case.

Finally, as it is clear in the above figure, the steady state of the power flow has higher values when frequency droop is implemented than when it is deactivated. This adds stress to the system and capacity limits of AC lines subject to the added stress must be respected when implementing control.
If frequency droop needs to be implemented, a compromise must be found between DC voltage stability, frequency stability and rotor angle stability while respecting all power system constraints. This approach needs to be implemented to enhance any aspect of power stability and it is currently under study.

Conclusion

Introduction of power electronics helps in power system stability enhancement when proper assessment and controls are applied. MTDC grid can be involved in stability enhancement since it provides wide control opportunities and flexibility. While AC networks have already well-established network codes, proper codes for DC grids are still required nonetheless to ensure MTDCs' usage leads to better AC/DC power system operation.
As was shown in the case studies, power converters' supplementary controllers have effects not only on targeted stability aspects but on other aspects as well. The need for a new and adapted approach is then

evident to avoid antagonist effects of future controllers. For optimal power stability improvement, local and wide-area measurements may be needed to perform best stability assessment due to observability issues. Most important is that, as opposed to conventional enhancement approaches, 'global' stability enhancement requires coordination of control from MTDC's potential controllers as was highlighted by the shown results.

Ongoing works are on establishing rigorous assessment approaches that allow to evaluate AC & DC power system stability to enhance it in a future step.

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