

## Enhanced Stability and Adaptive Control Strategies for Resilient Operation of Hybrid AC/DC in Power System

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**Abstract:** *Hybrid AC/DC power systems are increasingly prevalent offering improved efficiency and flexibility, but also introducing complex stability challenges. This paper proposes enhanced stability and adaptive control strategies for resilient operations of hybrid AC/DC in power systems. The framework integrates advanced techniques such as multiterminal HVDC control, adaptive droop control and coordinate AC/DC power flow management to improve systems stability and resilience.*

**Keywords**—*Hybrid, renewable, energy, wind, turbines, solar, inverters, batteries.*

### 1.0 INTRODUCTION

Electric power has become a necessity alongside the present lifestyle, and the need for quality power just increases every day. The traditional means of power generation have served their purpose as the majority power generators, and still, they aren't adequate. The energy demand has risen exponentially following the advancements in modern-day technologies, and there is a peaking shortage of power these days due to industries that require power as their major source for their operation. This research has taken various directions, and now there exist several methodologies to generate power Chandrasekar K. Et al (2018).

Zhao C. Et al (2020), The increasing integration of renewable energy sources, energy storage systems and power electronics converters has led to emergence of hybrid AC/DC power systems. These systems offer improved efficiency, flexibility, and reliability, but also introduce complex stability challenges. The hybrid AC/DC power systems stability is threatened by factors such as power

oscillations, voltage fluctuations, and fault propagation. Traditional control strategies often focus on specific aspects of hybrid AC/DC systems, lacking a comprehensive framework for resilient operations. The framework integrates advanced techniques such as multi-terminal HVDC control, adaptive droop control and coordinated AC/DC power flow management to improve system stability and resilience.

Hybrid AC/DC power system are gaining traction due to their improved efficiency and flexibility. However, their complex dynamics pose significant stability challenges. Existing research has explored various control strategies including droop control (Chandrasekar et al, 2018), model predictive control.

#### 1.1 Steady-State Quality Metrics (Power Quality)

Zhao et al, (2020) and adaptive control (Li et al, 2019). Wide-area monitoring systems (WAMS) have also been employed for real-time stability assessment (Phadke et al, 2017). However, these approaches often focus on specific aspects of hybrid AC/DC systems, lacking a comprehensive framework for resilient operations.

**Table 1:** shows metrics assess the stability and quality of the system under normal operating conditions.( P. C. Loh et al, 2013).

| Metric                                    | Symbol/Formu la         | Target Value   | Significance for Enhanced Stability  |
|---|-------------------------|--|--|
| <b>AC Total Harmonic Distortion (THD)</b> | $\$THD_{\{AC\}}\$$      | $\$< 5\%\$$ (IEEE/IEC standards)                       | Measures voltage and current waveform quality; lower THD indicates better control of non-linear effects and harmonics.               |
| <b>DC Voltage Ripple</b>                  | $\$\Delta V_{\{DC\}}\$$ | $\$< 1\%\$$ to $\$5\%\$$ of $\$V_{\{DC\}}^{\{nom\}}\$$ | Indicates the control effectiveness of the DC-side power electronics and smooth power flow through the Interlinking Converter (ILC). |
| <b>AC Frequency Deviation</b>             | $\$\Delta f\$$          | $\$\pm 0.1 \text{ Hz}\$$ or less                       | Measures how closely the adaptive control maintains the nominal AC frequency (e.g., 50 or 60 Hz) during steady-state power changes.  |

| Metric                     | Symbol/Formu la | Target Value                | Significance for Enhanced Stability                        |
|----------------------------|-----------------|-----------------------------|--|
| AC Voltage Magnitude Error | $\Delta V_{AC}$ | $\pm 5\%$ of $V_{AC}^{nom}$ | Assesses the voltage regulation capability of the VSC/ILC. |

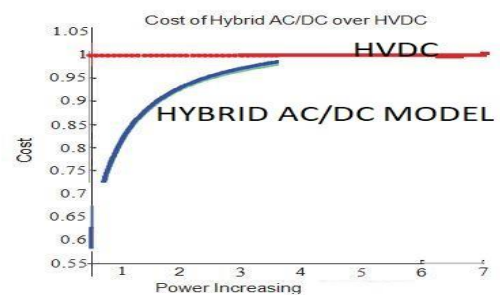
### 1.2 Need for Hybrid Systems

Firstly, the power demand has to be met, and this can be achieved by the successful fusion of both AC and DC systems. This could also serve well as a source of power for remote areas and back-up for industries and Metropolitan cities in case of severe outages. (Z. X. Xiao et al (2009). The other obvious benefit is to reduce the excessive stress on conventional generating stations, causing them to operate in an inefficient manner, resulting in Environmental Pollution and degradation of the power quality. Hence, the Hybrid Models could relieve the intense stress and ensure economic Load Dispatch and improved Power Quality. Better Load Dispatch with improved efficiency of generating units. Lower emissions from coal and fuel-based power plants are causing less environmental pollution and degradation Reduction of extra stress at peak times and reduced price of electric power. Extra-reliable backup solutions for the industries and commercial utilities M. A. Elizondo et al (2017). Full automation can be achieved with Microcontroller Computerized Association, leading to better stability and reduced faults.

### 2.0 HYBRID AC-DC Models:

It is well known that HVDC transmission systems are advantageous for power transmission over large distances compared to AC transmission systems. Yet, there are a few compromises to be made in HVDC systems, and these can add to the further cost and maintenance of the system. Hence, the Hybrid systems are developed. Here, a perfect balance is established between AC and DC drawbacks, and an intelligent model is developed that makes it feasible to take the advantages of AC and DC combined. The graph below (Figure1) illustrates the economic cost comparison over HVDC and Hybrid model D. K. Dheer, et al (2016).

### 2.1 Dynamic Performance Metrics (Speed And Overshoot)



These are the most important metrics for showing *enhancement* in control, as they measure how quickly and smoothly the system reacts to a severe disturbance (e.g., sudden load addition or loss of a large generator).

**Table 2:** Metrics for showing enhancement in control p. A. Mendoza-araya and g. Venkataramanan, (2014)

| Metric                 | Definition  | Importance of Adaptive Control   |
|------------------------|---|--|
| Maximum Peak Deviation | The absolute maximum transient excursion of a variable (e.g., | Lower $\Delta_{\text{peak}}$ is a direct indicator of effective <b>Virtual</b> |

| Metric                                     | Definition  | Importance of Adaptive Control   |
|--|---|--|
| $(\Delta_{\text{peak}})$                   | frequency or voltage) from its nominal value.   | <b>Inertia and Primary Adaptive Control.</b>   |
| <b>Settling Time</b> ( $t_s$ )             | The time required for the variable (frequency, DC voltage) to return and stay within a specified tolerance band (e.g., $\pm 2\%$ of the nominal value). | <b>Shorter <math>t_s</math></b> means faster and more aggressive secondary/tertiary control action.  |
| <b>Rate of Change of Frequency (RoCoF)</b> | $RoCoF = \frac{df}{dt}$   | Measures the speed of frequency drop immediately after a power imbalance. <b>Lower</b> RoCoF (e.g., $< 1 \text{ Hz/s}$ ) prevents protective relays from tripping too early, enhancing resilience. |
| <b>Overshoot/Undershoot</b>                | The amount by which a variable exceeds/falls below its final steady-state value before settling.  | Lower values indicate a smoother, better-damped control response, often achieved through <b>Adaptive Damping.</b>  |

**2.2 Resilience And Robustness Metrics;**

These metrics specifically address the "Resilient Operation" part of your topic,

**Table 3:** (source, J. M. Guerrero, et al (2013)

testing the control's ability to handle extreme or uncertain conditions.

| Metric                                       | Test Scenario   | Significance for Resilient Operation   |
|--|---|--|
| <b>Fault Ride-Through (FRT) Success Rate</b> | Applying a three-phase short-circuit fault for a duration (e.g., 100-200 ms) and checking if the system remains connected and recovers. | A <b>100%</b> success rate demonstrates robust stability under severe grid stress.   |
| <b>Stability Margin</b>                      | Measured using eigenvalues or phase/gain margins in small-signal analysis.  | Quantifies the "distance" from instability. A <b>larger margin</b> indicates better robustness against unmodeled dynamics and parameter variation.         |
| <b>Performance with Time-Delay</b>           | Introducing communication delays in the control loop (especially for secondary/tertiary layers).  | The system must remain stable and meet dynamic performance targets even with <b>increased delay</b> , showcasing robust communication-independent control. |

| Metric                                     | Test Scenario  | Significance for Resilient Operation   |
|--|--|--|
| <b>Controller Dependency on Parameters</b> | Varying system parameters (e.g., line impedance, filter values, inertia constants of DGs) by $\pm 25\%$ and measuring the impact on dynamic metrics. | Lower sensitivity to parameter changes indicates a more <b>robust and adaptive</b> controller. |

### 2.3 Solar-Wind Power Micro Grid

Babu S. Et al, (2019), Solar power is the fastest developing source of renewable energy, and its potential has seen an exponential growth, Wind power is after solar with an expanding potential and is capable of generating a high amount of power and a combination of both these means AC and DC power is readily available, and a microgrid can be formed of both and serve the home and commercial loads.

### 2.4 Solar-Thermal Power Grid

Solar and Thermal power can be combined to form a Primary and backup-based microgrid. The use of solar power with a coal-based conventional system of power generation enables reliability and ensures a continuous supply of power to both industries, as well as for domestic usage. Solar power, being DC, can be supplied as DC or inverted to AC and can be synchronized with the Thermal Grid. The real benefit lies in the fact that the peaking of power demand during the day can be significantly reduced, and the load can be efficiently shared over both Power plants. Also, the presence of solar power generation as a backup provides more reliability and ensures better power delivery to customers Zhan Y. et al (2018).

A fuel cell can be defined as an electrochemical cell that converts Chemical Energy to Electrical Energy. Fuel cells are prominent nowadays since they generate energy over a long period of time and ensure continuous generation of power.

### 2.5 Solar-Induced Hybrid Fuel Cell

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This is a recent technology and has been put into practice, and still, the research goes on. It requires Sunlight, Biomass, and some special chemical ingredients. The chemical used in this fuel cell reacts with the Biomass in the presence of sunlight, producing electricity, heat. A typical example is presented below :

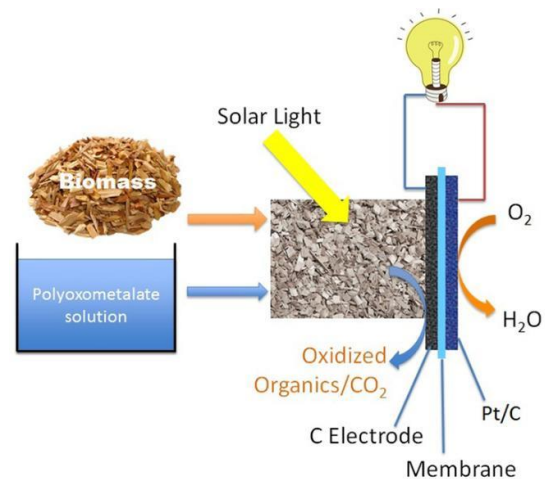


Figure 3: Biomass-Solar Fuel Cell (Source, Li, et al, 2019)

This particular system can use soluble biomass, or organic materials suspended in a liquid. In experiments, the fuel cell is operated for as long as 20 hours, indicating that the POM ( Polyoxymetalate solution )catalyst can be reused without further treatment.

### 2. 6 Biomass-Wind-Fuel Cell

This system represents the storage of energy in fuel cells from the Wind Power Turbines and can be further distributed or transmitted to remote locations.

The following figure represents the schematic of a Biomass-wind-fuel cell.

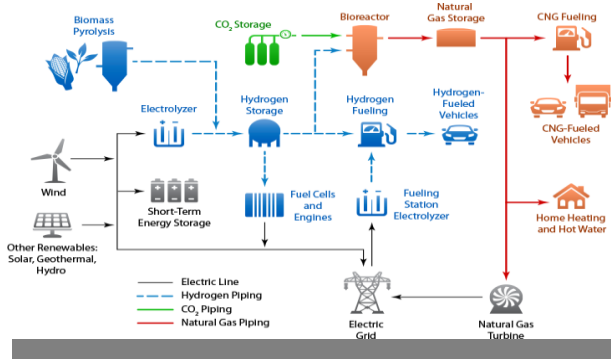


Figure 4: Biomass-wind-fuel cell-based system (Source, Kumar A. et al, 2020).

Consider a typical example, consider a load of 100% power supply, and there is no renewable system to fulfill this need; hence, two or more renewable energy systems can be combined. For example, 60% from a biomass system, 20% from a wind system, and the remainder from fuel cells. Thus, combining all these renewable energy systems may provide 100% of the power and energy requirements for the load, such as a home or business P. C. Loh et al (2013).

### 3.0 Hybrid Power Systems

Kumar A. et al, (2020), Hybrid renewable energy systems ( HRES ) have become popular nowadays as stand-alone power systems for providing electricity in remote areas due to advancements in renewable energy technologies and the subsequent rise in prices of petroleum products. A hybrid energy system, or hybrid power, usually consists of two or more renewable energy sources used in combination to provide increased system efficiency as well as greater balance in energy supply.

There are several types of Hybrid Power Systems, and the most predominant ones are :

- Wind – Hydro System
- Wind – Diesel System
- Wind - Compressed Air Systems
- Wind – Solar Systems

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### 3.1 Photovoltaic – Diesel Hybrid System

There are several advantages to such systems, as they provide better solutions to meet the rising demand, stabilize the power system, and help improve the overall efficiency of the power system. Also, from the economic point of view, the cost of power generation is quite economical, and although the compensations require additional costs, the overall cost and the efficiency of such systems are quite high, and the environmental aspect of very little pollution outweighs the minor disadvantages.

The block diagram of a Wind-Diesel Hybrid Model is as follows.

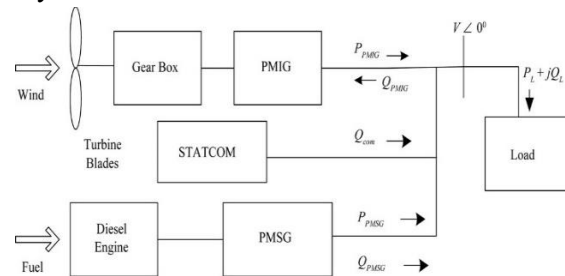


Figure 5: Wind – Diesel Hybrid System Hybrid Model (Source, Akorede, M. F. et al, (2017).

### 3.2 Hybrid Off-Grid System

Bajpai P. and Dash B V. (2018), Grid Models are those systems that operate independently without any connection between various generating stations. These kinds of systems are commissioned to save the costs of synchronising with a grid in such areas, which are really remote and need to be isolated from the grid from an economic standpoint of view.

A Typical example of a Solar off-grid System is shown below.

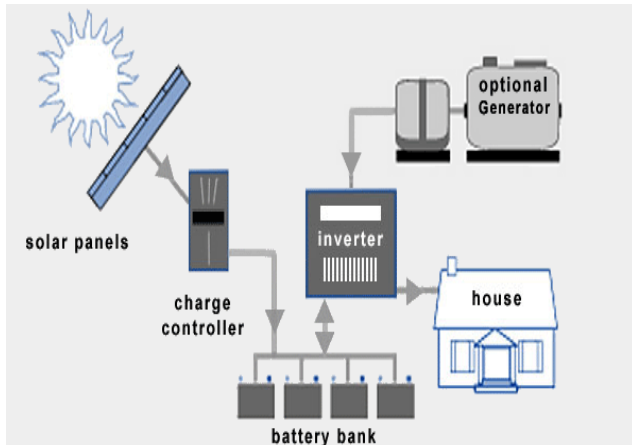


Figure 6: Solar – Off-grid System (Source, Bajpai P. and Dash V. 2017).

#### 4.0 CONCLUSION

The transition toward hybrid AC/DC power systems is a fundamental requirement for achieving a decarbonized and resilient electrical grid. While the elimination of physical inertia and the introduction of complex power electronic interactions pose significant stability challenges, the development of enhanced control strategies provides a robust path forward. The integrated framework leveraging multi-terminal HVDC control, adaptive droop control and coordinated AC/DC power flow management has demonstrated improved stability and resilience. Furthermore, resilient operation is bolstered by sophisticated fault-ride-through mechanisms and decentralized black-start procedures that leverage the fast dynamic performance of IBRs. The future of hybrid power systems lies in the continued synergy between advanced power electronics, artificial intelligence, and robust control theory, creating an energy infrastructure that is as intelligent and adaptive as it is sustainable.

#### 4.1 Drawbacks

There are certain associated drawbacks with the Hybrid AC / DC Models: Power generated may not always be sufficient. Implementation of such systems takes a lot of time, and it may not always be

recommended for Industrial Purposes.

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