New Control Strategy Based PV- STATCOM for Mitigation of Power Oscillation Damping

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***Abstract-* Flexible AC Transmission Systems (FACTS) like the Static Synchronous Compensator (STATCOM) are commonly employed to enhance the performance and stability of power networks. This study introduces a photovoltaic (PV)-based STATCOM system, referred to as PV-STATCOM, which incorporates a Fuzzy Logic Controller (FLC) to effectively mitigate power oscillations. The core functionality of the proposed system involves temporarily suspending the PV system's real power output during daytime disturbances. When oscillations are detected, the PV inverter halts energy production for a brief period—typically a few seconds—and instead operates in a mode that utilizes its full capacity to dampen the oscillations. Once stability is achieved, the inverter resumes its power generation role in a gradual manner, ensuring a smooth transition and quicker recovery compared to traditional grid code-based responses.**

During nighttime, when the PV system does not generate real power due to lack of sunlight, the inverter continues to function fully as a STATCOM for oscillation damping. Simulation results conducted in MATLAB confirm that the proposed system significantly improves power transfer capacity under various dynamic conditions. Additionally, the PV-STATCOM offers a cost-effective solution compared to conventional STATCOM devices, potentially resulting in considerable savings for utilities involved in power generation and distribution.

***Index Terms--*Photovoltaic solar power systems, voltage control, reactive power control, power oscillation damping, FACTS, STATCOM, power transmission, PV ramp rate Fuzzy logic controller.**

I INTRODUCTION

In long transmission lines, one of the major hindrance for transferring power is, power oscillation (0.1 HZ to 2 Hz) [1-2]. These low frequency oscillations due to electrical and mechanical factors are to be damped for efficient power transfer in a transmission system. The conventional systems use Power System Stabilizers (PSS) along with synchronous generators for damping these oscillations [1-2]. However, enhanced power transfer capability in transmission lines and damping of power fluctuations are achieved by effective utilization of power electronics based Flexible AC Transmission System (FACTS) devices [3-5]. Performances of various FACTS devices such as Static-VAR-Compensators (SVC),STATCOM,Unified Power Flow Controller (UPFC), Unified Power Quality Controller (UPQC) , Thyristor Controlled Series Compensator (TCSC) and Convertible StaticCompensator (CSC) capable of POD areexplained in various works [6-10].

Solar farms oflarge scale are being extensively utilised worldwide and connected to the main grid. These include Bhadla Solar-Park in India (2245 M W), Pavaganda Solar-Park in India (>2000 M W), Noor Abu Dhabi in UAE (1177 MW), NP Kunta in India (978 M W), Datong Solar-Park in China (1000 MW), Rewa Ultra Solar-Park in India (750 MW) Mount Signal Solar (794 MW) in US, Huanghe Solar-Park in China (2200 MW) and Benban Solar-Park in Egypt (>1650 MW)[11]. Solar farms with PV inverters have capability to inject power which is inertia less. This feature enables PV Solar- farms to have potential to reduce power system in-stability in the grid.

This paper analyses the effectiveness of the proposed PV inverters in solar-farms as STATCOM which is termed as PV-STATCOM. The dampingof power oscillations (POD) and enhancing the capability of transfer of power in a transmission system is achieved throughmodulating the reactive power by diverting complete capacity of the inverter at nighttime. Similarly, entire inverter capacity is diverted for POD at day time by discontinuing its real power generation function very briefly. These functions are demonstrated on a Single-Machine Infinite-Bus (SMIB) system [23], Two-Area Four-machine system [1-2], and 12-bus system [28] by using MATLAB/SIMULINK. The POD controller is designed using simplex optimization method embedded in MATLAB [24]. The small signal Residue Analysis technique demonstrated for arriving at the best position of PSS vide [25-27] is considered here to examine the efficacy of positioning PV-STATCOM in a transmission system. Feasibility to utilize Fuzzy control for realizing the controller has also been explored and demonstrated using MATLAB software.

II. PV-STATCOMCONCEPT

Typical active power generation of a PV inverter(**p**)when sun light is available in a day and the reactive power capability**(q)**in remaining period when sun light is not available is illustrated in Fig 5.1. This smart inverter which will act as Photovoltaic -STATCOM can function in two modes as shown in the figure: -

Partial mode. The capability of PV-inverter available after generating real power output is used for functioning as STATCOM in case of 'partial PV-STATCOM mode'. This mode is employed in daytime [1].

Full mode.In Full PV-STATCOM mode pf operation, full capability of PV inverter of the solar-farm isexploited to function as STATCOM. Full mode of operation is utilized in night time[1].

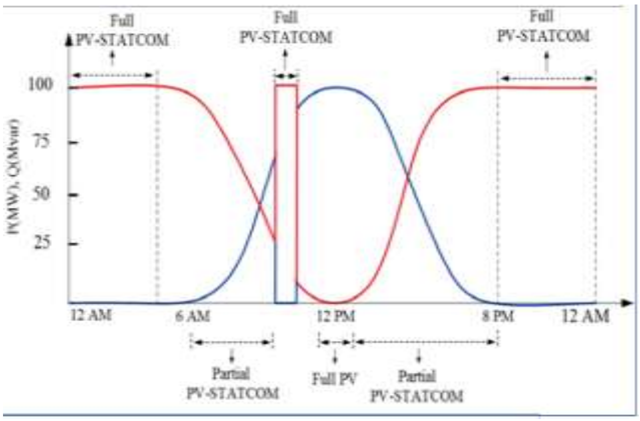

Fig-5.1. Active-reactive power output of PV inverter(24 hours ideal distribution on a sunny day)

During daytime, the real power generation function is interrupted when ever any undesirable power oscillation (low-frequency) owing to any sort of system interference are identified. Accordingly, the PV inverter will act as PV- STATCOM with complete inverter power is used for modulating reactive power. Therefore, reactive-power up to maximum capacity of the PV-inverter would be exploited for damping the oscillation depending upon system needs. As soon as damping is achieved, the PV inverter will be restored to function in normal mode to generate active power. The PV inverter restores its power generation in a ramped fashion to the previous level before any interference while damping by the PV-STATCOM will continue in Partial mode. Whereas, at night when no sun light is available, the full mode of operation of PV-STATCOM is continuously available. During that period, the PV- inverter utilizes its full capacity for reactive power modulation and thereby achieving power oscillation damping. Besides these two modes, invertercan function in 'full-mode', where, generation ofactive power depends on irradiance of the sunlight at unity power factor (UPF)without any"smart functions".

III. Single Machine Infinite Bus (SMIB) System: FIG3.2 Diagram of a huge alternator/synchronous generator feeding an Infinite-Bus using a long transmission line (600 km)[23]. In the figures, a PV solar farm (100 MW) acting as STACOM is positioned at Bus 2 ,which is mid-point of the line.

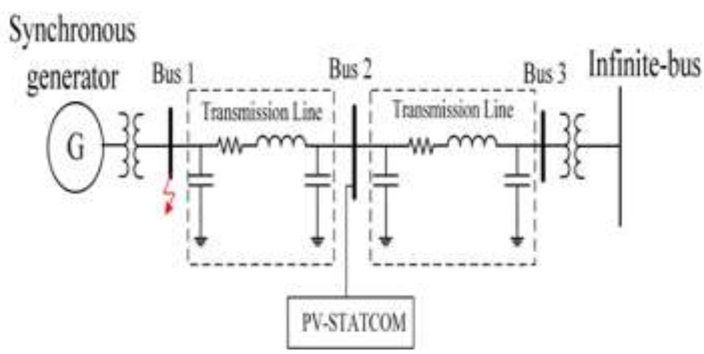

Fig. 3.2 SMIB system with PV-STATCOM at Mid Point

Two-Area Four-Machine system. A Two-Area (A and B) system with four Machines (G1-G4) connected through a long 220 km transmission line with a PV-STATCOM (100 MW) at the midpoint

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between bus 7 and 9 is illustrated in fig 5.3[1-2].In this two-area four machine system, the machines are not installed with Power System Stabilizer (PSS). The parameters as given in [1-2] and [23] are considered in this paper for calculations. In case of Two-Area systems, oscillations due to local inertial fluctuations as well as inter-area fluctuations will be affecting thetransfer of power [1-2].

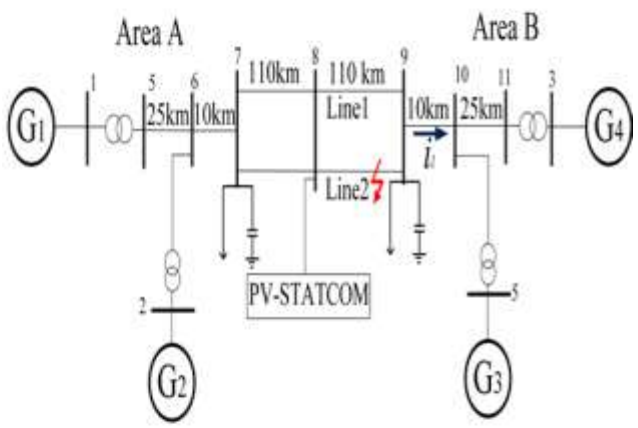


Fig 3.3: 12 Bus FACTS power system:

Impact of FACTS controls is studied widely using 12 bus FACTS power system. Efficiency of the controller has been demonstrated by performing damping of power oscillations with PV-STATCOM on 12 bus system with various oscillation modes. In this system no Power Stabilizer Systems are considered on machines.

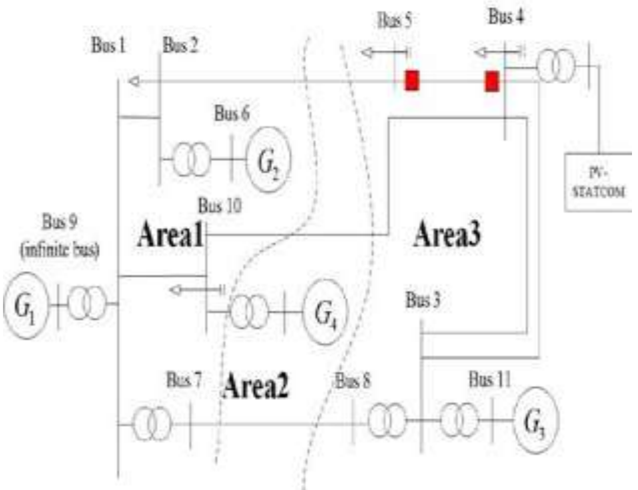


Fig. 3.4. 12 bus FACTS power system with 100 MW PV solar systems at bus 4

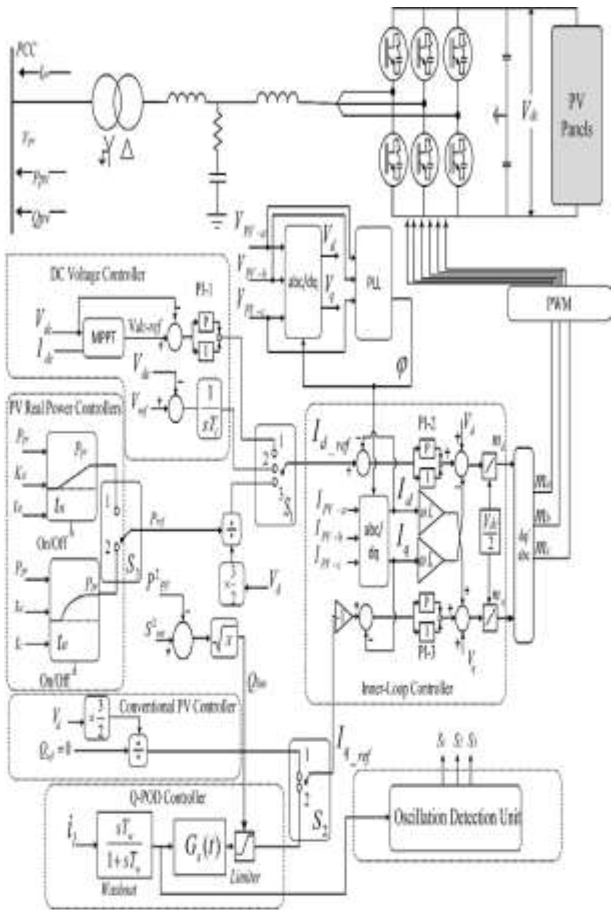


Fig. 3.5 PV-STATCOM controller

PV-STATCOMMODELING. Varioussub-units of the PV-STATCOM controlleras illustrated in Fig. 3.5 are described below.

PV Panels and Inverter.An equivalent panel model in which dc current out of PV array based on its V-I characteristic is represented by ‘PV Panel’ [30]. The PV solar inverter is athree phase Voltage Controlled Inverter controlled by six pulseswith a DC link capacitor [31]. This VSI type photovoltaic inverter is inserted in to power transmission line via an Inductor-Capacitance-Inductor (LCL)-filter [32]. Various parameters at the PCC are represented with symbols Vpv, Ipv , Ppv and Qpv depictsvoltage, current, real power and reactive powerof the inverter.

Inner Loop Controller. The parameters for controllingactive and reactive power using decoupled ‘d-q’ components is provided by inner loop controller . The same is achieved using respective reference currents of direct (d) and quadrature(q) components Id-ref and Iq-ref respectively [31]. Further, the inner loop controller derives modulation index m_d and m_q. This phasor indices undergo transformation again with the help of inverse Park transformation (dq/abc) andgenerate three phase modulation index 'm_a', 'm_b' and 'm_c'. The indices (m_a,m_b and m_c) derived by inverse Park transformation are used for generating triggering pulses for IGBTs in the Voltage Source Inverter using suitable Pulse Width Modulation (PWM)method [29]. The Parks transformation ('abc' / 'dq)block and Phase Locked Loop (PLL) blockare designed as demonstrated in [31]. 'Vdc' in the fig 5.5 represents voltage of DC link in PV-STATCOM. 'Vd', 'Id','Vq' and 'Iq' represents d and q axis voltage (V) and current (I).

DC Voltage Controller. Two sub unitsof DC voltage controller are as follows [32] :-

i) Maximum Power Point Tracker (MPPT) andProportionate Integrate controller.

ii) DC voltage controller.

The MPPT block utilizes 'Vdc' and 'Idc' to create the reference voltage 'Vdc_ref,' which ultimatelygenerates 'Id-ref' for the inner-loop controller while functioning underconventional PV mode, as per the Voltage-Current (VI) characteristic of the Photovoltaic panels. When the system is in STATCOM mode, S1changes from position 1 to 2. Further, DC voltage 'Vdc' gets limited to open circuit voltage of the PV panel such that power (real)output from inverter is disabled [34]. PV panel open-circuit voltage depends on the incident irradiance and temperature and varies accordingly. In case of a specific PV panel in the solar-farm, 'V_{ref}' as given in the figure. 5.5 is taken as the highest open-circuit voltage out of different power-voltage specifications (provided by the manufacturer) for different values of realistically prevalent temperatures and solar irradiance [30].

Conventional PV controller. This controller is responsible for controlling reactive component of the inverter output in such a way thatphotovoltaic arraysgenerates real power or,in other way, the generated power factor is unity [31]. Theconventional controller is utilised only inusualfunctioning of the power system where power factor requirement isunity [31], [33], [35]. Here, Q or reactive component is set as 'zero' during the steady state operation and hence 'Iq-ref' will be zero. Further, it is pertinent to note that this controller will be disabled whenpower instabilities/fluctuations are encountered.When power oscillationsoccur, Q-POD controller generates 'Iq_ref' in a closed-loop manner.

IV. FUZZY CONTROLLER:

The word Fuzzy means vagueness. Fuzziness occurs when the boundary of piece of information is not clear-cut. In 1965 Lotfi A. Zahed propounded the fuzzy set theory. Fuzzy set theory exhibits immense potential for effective solving of the uncertainty in the problem. Fuzzy set theory is an excellent mathematical tool to handle the uncertainty arising due to vagueness. Understanding human speech and recognizing handwritten characters are some common instances where fuzziness manifests.

Fuzzy set theory is an extension of classical set theory where elements have varying degrees of membership. Fuzzy logic uses the whole interval between 0 and 1 to describe human reasoning. In FLC the input variables are mapped by sets of membership functions and these are called as "FUZZY SETS".

Fuzzy set comprises from a membership function which could be defines by parameters. The value between 0 and 1 reveals a degree of membership to the fuzzy set. The process of converting the crisp input to a fuzzy value is called as "fuzzificaton." The output of the Fuzzier module is interfaced with the rules. The basic operation of FLC is constructed from fuzzy control rules utilizing the values of fuzzy sets in general for the error and the change of error and control action.

The results are combined to give a crisp output controlling the output variable and this process is called as "DEFUZZIFICATION."

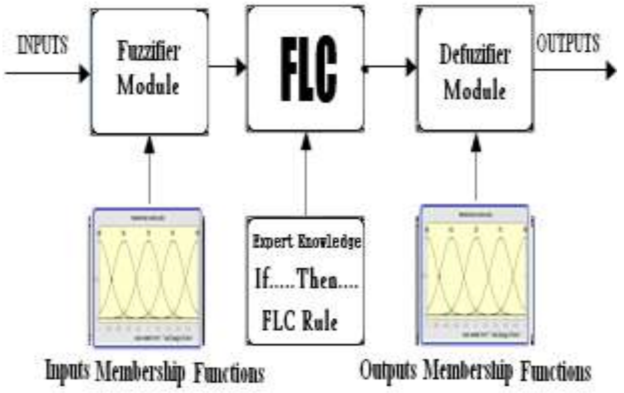


Fig 4.1: block diagram of fuzzy logic Controller

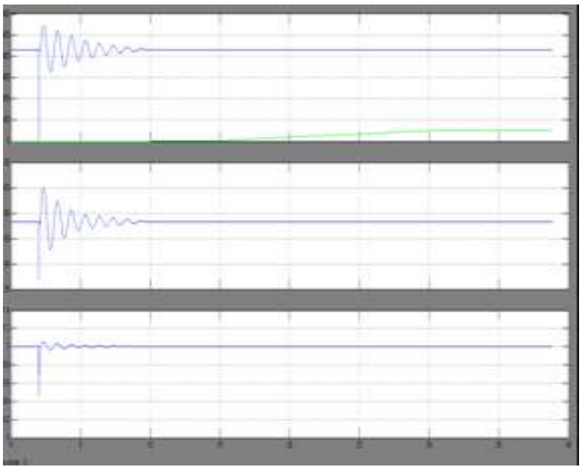


Fig. 4.3 (a) Midline and PV system real powers, (b) PV-STATCOM reactivepower, (c) Midline voltage during POD and normal ramped power restoration

IV.Simulink Model and Results

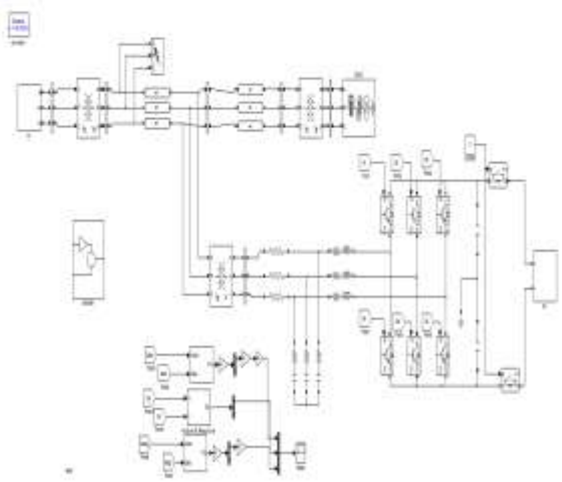


Fig4.1Simulink Block Diagram

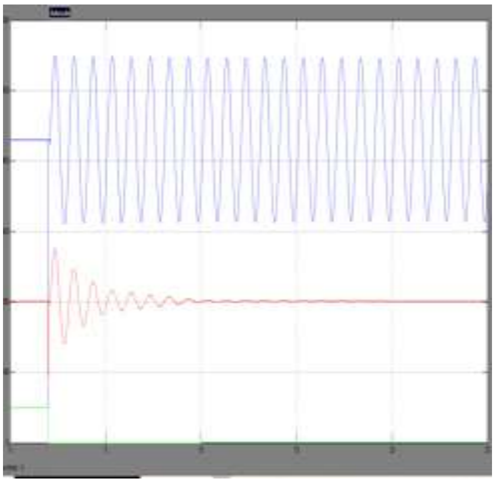
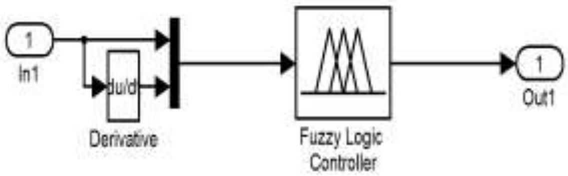


Fig. 4.2. Maximum power transfer capability of the SMIB system



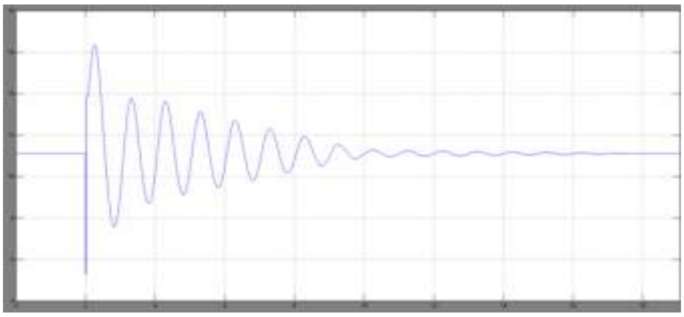


Fig. 4.4. Nighttime using fuzzy logic controller (a) Midline real power without POD with PV-STATCOM control, (b) Midline real power with Full PV-STATCOM POD Control, (c) PVSTATCOM reactive power

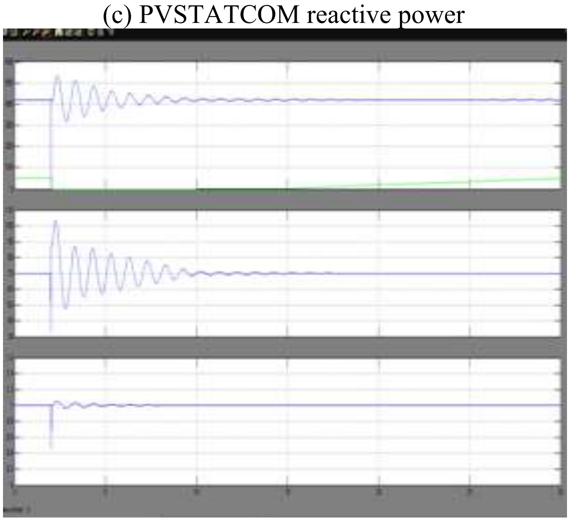


Fig. 4.5(a) Midline and PV real power, (b) PV reactive power, (c) Midlinevoltage during POD and power restoration in a fast ramped manner.

CONCLUSION

This paper presents an innovative approach where a photovoltaic (PV) solar farm is operated as a Static Synchronous Compensator (STATCOM), known as PV-STATCOM, integrated with a Fuzzy Logic Controller (FLC). The proposed PV-STATCOM is specifically designed for Power Oscillation Damping (POD) in electrical power systems. Upon detection of oscillations caused by disturbances or external interference, the PV-STATCOM temporarily halts its real power generation function—typically for around 15 seconds. During this period, the full inverter capacity is repurposed to regulate reactive power, effectively damping the oscillations. This enables the PV system to function as a STATCOM, improving system stability. At night, the inverter's complete capacity can be used for reactive power modulation. During the day, only the portion of inverter capacity not used for real power output is employed for this purpose.

Once the oscillations are adequately damped, the system gradually resumes its real power generation, returning to its pre-disturbance state. This gradual or ramped transition ensures a smoother and quicker recovery of grid power compared to conventional grid code-based restoration techniques. To validate this concept, simulations were conducted on multiple systems, including a Single-Machine Infinite Bus (SMIB) system, a Two-Area Four-Machine setup, and a 12-bus network using MATLAB/SIMULINK. The POD controller was optimized using the simplex method available in MATLAB. Additionally, small-signal residue analysis was performed to evaluate optimal placement of PV-STATCOM units. The fuzzy logic-based control scheme was also developed and tested within the MATLAB environment.

Performance evaluations indicate significant improvement in power transfer capability. Economically, PV-STATCOM offers a cost-effective alternative to traditional STATCOM devices. Since it utilizes the existing solar farm infrastructure—such as transformers, substations, protection devices, and bus networks—the capital investment is significantly lower, estimated at less than 10% of the cost of a standalone STATCOM of similar rating. Adopting PV-STATCOM technology presents a promising opportunity for solar farms to diversify their functionality and generate additional revenue by offering grid support services. Nevertheless, implementing such systems would require coordinated agreements among stakeholders, given the regulatory frameworks governing power generation and distribution.

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