SmartParks for Short Term Power Flow Control in Smart Grids

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Abstract— **Among other functions, the smart grid is a vehicle to maximize the penetration of wind power by exploiting the use of energy storage devices in order to maximize the utilization of renewable energy and bring about maximum reduction in emissions. Large number of electric vehicles in a parking lot enabled to carry out vehicle-to-grid (V2G) transactions has been termed as a 'SmartPark' by the author. The use of vehicle-to-grid technology, information technology and advanced computational methods can provide short term real and reactive power support to overcome the drawback of the intermittent nature of renewable sources of electricity. This paper presents the intelligent control of SmartParks to enhance a smart grid's capability to compensate and mitigate active and reactive power fluctuations caused by the variability in wind power penetration in selected transmission lines and network buses.**

Keywords – Energy storage, plug-in electric vehicles, power flow control, renewable energy, SmartParks, smart grid, vehicle-to-grid (V2G), wind power,

I. INTRODUCTION

The smart grid can be viewed as a digital upgrade of the existing electricity infrastructure to allow for the dynamic optimization of current operations as well as the incorporation of dynamic gateways for alternative sources of energy production and storage. The number of plug-in electric vehicles (PEVs) entering the market is increasing and these vehicles could participate in providing grid services through the vehicle-to-grid technology in a smart grid framework. Most personal vehicles in the US are parked more than 95% of the day and generally follow a daily schedule [1], their predictable nature can be utilized successfully in vehicle-to-grid (V2G) transactions.

Using V2G, PEVs can provide many grid services, such as regulation and spinning reserve [1], [2], load leveling [3], serving as external storage for renewable sources [4], generating revenue by buying and selling power at different times according to variable price curves [5], [6], and providing reactive power support [7]. Battery energy storage and shunt flexible AC transmission system devices such as static var compensators and static compensators (STATCOMs) are capable of very fast and accurate active and reactive power compensation [8], [9]. However, the main drawback of such devices is their high cost and non-mobility.

A large number of electric vehicles in a parking lot enabled to carry out vehicle-to-grid transactions has been termed as a 'SmartPark' by the author. The PEVs, while parked in a SmartPark, contain a significant amount of active and reactive power potential and can be utilized for meeting the grid's requirements with little significant infrastructure cost.

Due to the intermittent nature of wind power generation, several problems can occur in grid connected mode, including power oscillations and transmission line power flows exceeding their limits. This may result in power system instability [10], [11]. A wind farm with energy storage that maintains a constant power output can be used to mitigate these problems. Integrating energy storage systems reduces the uncertainty in wind power generation and increases grid reliability and security. Combining energy storage with wind farms also reduces operating costs by mitigating possible price hikes or sags [12]. The energy storage unit is generally connected to the dc link in between the rotor and grid-side inverters of the doubly-fed induction generator (DFIG) [8]. However, if the wind farm is large and consists of several DFIGs, the required number of energy storage units and converters will also be large.

The advantage of using SmartParks for voltage support is that reactive power can be injected to the grid without lowering the battery's state of charge (SOC). A very small amount of real power will be lost during this reactive power transaction process, so the vehicles' batteries will have to supplement the difference. However, for such a small amount of real power loss, the net reduction in the state of charge of the individual batteries will be negligible. Therefore, only a centralized controller will be needed at the SmartParks to make this idea a reality. With that control, it is possible for these SmartParks to behave like virtual STATCOMs.

Utilizing plug-in electric vehicles (SmartParks) to minimize power losses and voltage fluctuations in a Smart Grid was proposed in [13]. Using SmartParks (plug-in electric vehicle parking lots) as virtual STATCOMs for reactive power compensation was proposed in [14], and their use as shock absorbers for damping power oscillations in transmission lines connected to a wind farm was proposed in [15].

This paper presents the intelligent control of SmartPark(s) to absorb and inject power (active and reactive) in a smart grid with integration of a wind farm. Results are presented to illustrate that with appropriate control of SmartParks

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fluctuations/deviations in active power and voltages in selected transmission lines and buses, respectively, caused by wind power fluctuations can be mitigated.

II. SMART GRID TEST SYSTEM

The smart grid test system used in this study (Fig. 1) is a modified 12-bus multimachine power system [16] with three generators (G2, G3 and G4), an infinite bus (G1) and three interconnected areas. Generator G4 is a doubly-fed induction generator-based wind farm. A typical city will contain several SmartParks distributed throughout the city one to a few miles apart. To represent this, six three-phase PEV parking lots are added to this system in Area 2 to bus 13. Bus 13 is an additional bus added to the original 12-bus system in order to connect the plug-in electric vehicle parking lots. Bus 13 is connected to bus 6 through 22 kV/230 kV step-up transformers.

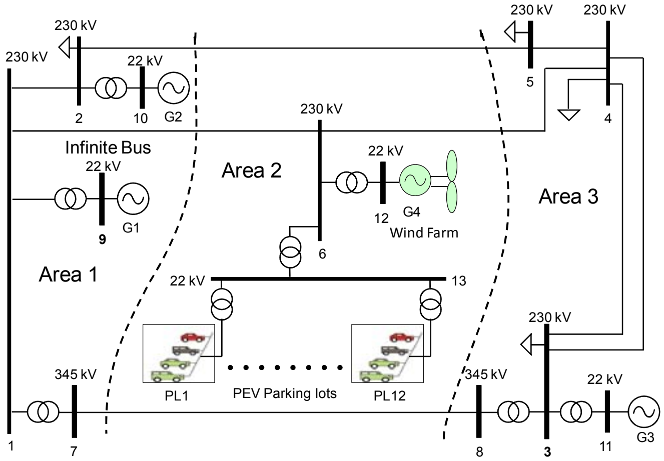

Figure 1. The 12-bus system with twelve SmartParks indirectly connected to bus 6.

The DFIG wind farm uses back-to-back PWM converters for variable speed wind power generation. The control objective of the grid-side converter is to keep the dc link voltage constant regardless of the magnitude and direction of the rotor power. A stator-oriented vector control approach is used in which the direct axis current controls the dc link voltage and the quadrature axis current controls the reactive power and, in turn, the voltage at the point of common coupling. The objective of the rotor-side converter is to control the active and reactive power from the stator. This is achieved by situating the d-axis of the rotor reference frame along the stator flux vector. The q-axis current reference is generated directly from the commanded electrical power, and the d-axis current reference is generated from the stator reactive power command. The electrical power command is generated from the optimum operating point-tracking strategy discussed in [17], when the wind speed is below a certain value. The pitch control does not work at that time, and the wind turbine captures the maximum possible energy at that wind speed. However, if the wind speed exceeds a certain value, the pitch control limits the power generated by the wind turbine.

The SmartPark model in this paper is represented by a battery followed by a bidirectional three-phase inverter. The inverter generates a 2.08 kV three-phase line-to-line rms voltage, which is then passed through a 2.08kV/22kV step-up transformer and connected to the SmartPark bus (bus 13 in Fig. 1). Between the inverter and the transformer is a small (0.5mH) inductance. The control of the inverters is designed in such a way that each inverter can draw ±20 MW of active power. Considering that each vehicle can draw ±25 kW, each SmartPark in this paper represents 800 aggregated vehicles. Here, the '+' sign indicates that the vehicles are injecting power to the grid, i.e., they are in discharging mode, and the '-' sign indicates that they are absorbing power from the grid, i.e., the vehicles are in charging mode. The control strategy for the SmartPark is presented in Fig. 2. In the *d-q* reference frame, the active and reactive powers coming out of the inverter are [18]:

$$P = (3/2) \cdot (v_{qs} i_{qs} + v_{ds} i_{ds}) \tag{1}$$

$$Q = (3/2) \cdot (v_{qs} i_{ds} + v_{ds} i_{qs}) \tag{2}$$

In the synchronous reference frame, the peak line-to-neutral voltage is in the *q*-axis, and $v_{ds} = 0$. Therefore, the basis of the control is to command the currents in response to the demanded power:

$$i_{qs}^{*} = (2/3\sqrt{2}) \cdot (P^{*}/v_{peak}) + (K_i/s) \cdot (P^{*} - P) \tag{3}$$

$$i_{ds}^{*} = (2/3\sqrt{2}) \cdot (Q^{*}/v_{peak}) + (K_i/s) \cdot (Q^{*} - Q) \tag{4}$$

The first components of (3) and (4) are based on the power equations (1) and (2), in which v_{peak} is a filtered version of the line-to-neutral rms voltage. This portion creates a quick response to sudden changes in commanded power. The integral term trims out the steady-state error. As shown in Fig. 2, a limit is placed on the commanded current, thus preventing integrator windup. The commanded *q*- and *d*-axis currents are then transformed to *a-b-c* variables in which delta current-regulation controls the converter transistor switches.

A SmartPark's duration of operation (t_f-t_i) can be determined using (5). $P_{wind}(t)$ is the wind power at time t; P_{ref} is the average wind power generation; q_i and q_f are the initial and final SOC at times t_i and t_f, respectively; and $v(q)$ is the battery voltage as a function of the SOC. q_f is limited by the minimum and maximum SOC (SOC_{min}, SOC_{max}).

$$\int_{t_i}^{t_f} (P_{wind}(t) - P_{ref}) \cdot dt = \int_{q_i}^{q_f} v(q).dq \tag{5}$$

The entire smart grid test system is modeled on a real-time digital simulator (RTDS) platform [19]. The simulations of the DFIG, the rotor-side and grid-side inverters and the vehicle inverters all are carried out on the giga processor RTDS cards using the small time step (1.5 μs) simulation.

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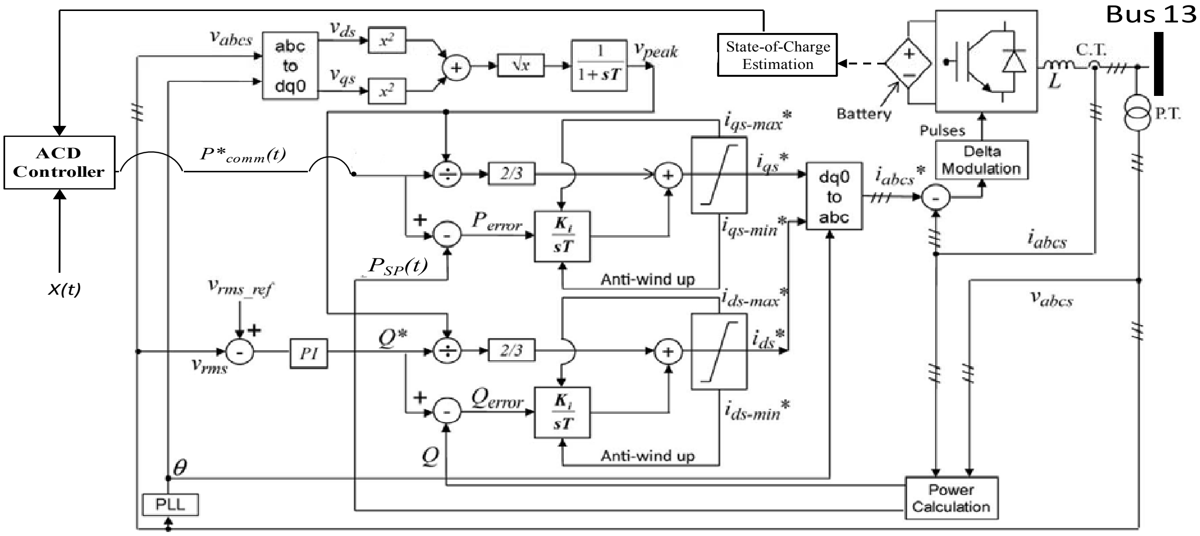

Figure 2. The current control strategy for the SmartParks (control for active power control).

III. MITIGATION CONTROLLER FOR ACTIVE POWER FLUCTUATIONS

The smart grid test system used in this study (Fig. 1) is a modified 12-bus multimachine power system [16] with three generators (G2, G3 and G4), an infinite bus (G1) and three interconnected areas. Generator G4 is a doubly-fed induction generator (DFIG)-based wind farm. The SmartParks in sink/source mode absorb/inject power, $P_{SP}(t)$, respectively, in order to reduce power fluctuations in transmissions 6-4, ($P_{6-4}(t)$), and 1-6, ($P_{1-6}(t)$), connected to the wind farm at bus 6An adaptive critic design (ACD) based wind farm-SmartPark coordinating controller with foresight that is suitable for dynamic optimal control is developed in this study. Adaptive critic design is a powerful computational approach that can determine optimal control laws for a dynamic system in a noisy, nonlinear and uncertain environment [20]. Compared to classical control and dynamic programming-based approaches, ACD is a computationally inexpensive method for solving infinite horizon optimal control problems. With ACDs, no prior information is needed about the system to be controlled, and optimal control laws can be determined based on measurements. The ACD methods adapt two subsystems, an actor and a critic. The actor receives the states of the system (wind speed, power flows, etc.) and dispenses the control signals (SmartPark charge/discharge commands). The critic learns the desired performance index for some function associated with the performance index and evaluates the overall performance of the system [20], [21]. The objective of ACD is to solve the Hamilton-Jacobi-Bellman equation through the two subsystems (actor-critic networks).

The action dependent heuristic dynamic programming type adaptive critic controller (Fig. 3) is developed in this study to mitigate power fluctuations. The utility function, $U(t)$, in Fig. 3 is given in (6) below.

$$U(t)=\alpha_1\,|P_{1-6}(t)-P_{1-6-ref}\,|+\alpha_2\,|P_{6-4}(t)-P_{6-4-ref}\,|+\alpha_3\,|\,\Delta SOC(t)\,| \tag{6}$$

The utility function is composed of the sum of three terms with weightings α_1, α_2 and α_3. The first two terms are the transmission line power fluctuations in lines 1-6 and 6-4. The third term represents the anticipated deviation in the SmartPark's SOC ($\Delta SOC(t)$) from its maximum and minimum SOC limits, which are estimated based on the forecasted wind power output over the following several seconds.

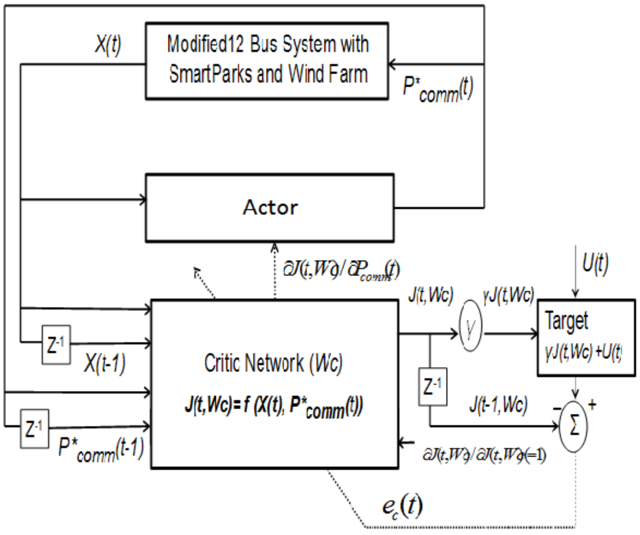

Figure 3. A dynamic optimal charge/discharge power command ($P^*comm(t)$) controller.

IV. SMARTPARK CONTROL FOR GRID VOLTAGE SUPPORT

When the SmartParks are used in voltage control mode, an additional voltage control loop is used in the control strategy, which is otherwise similar to that of an individual vehicle inverter. In voltage control mode, the bus rms voltage is first compared with the reference voltage, and the error is passed through a PI controller to generate the reactive power command for the SmartParks. This control strategy is presented in Fig. 4.

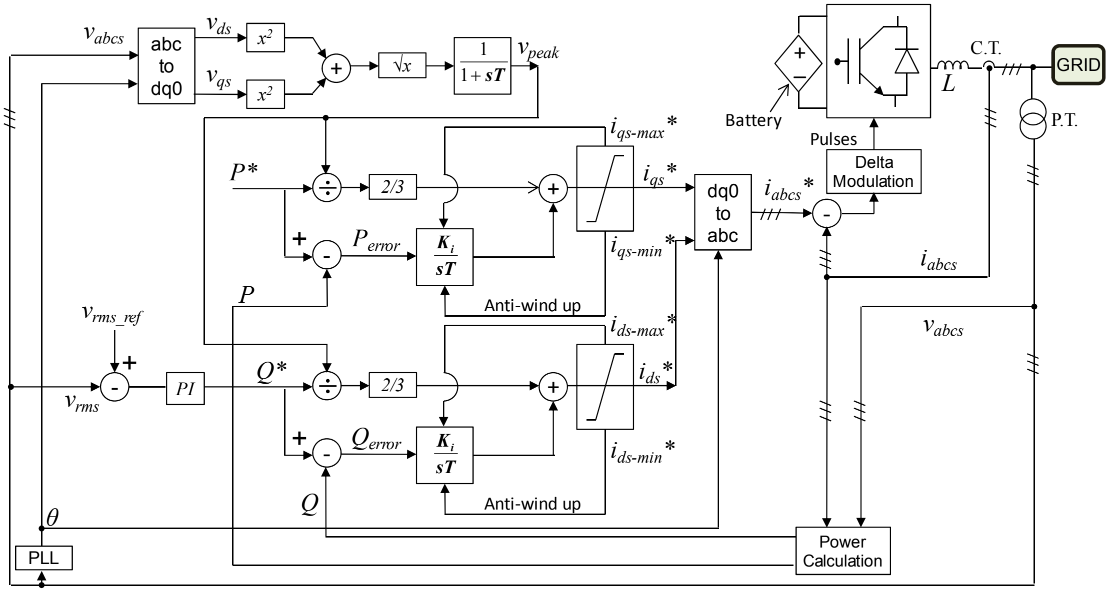

Figure 4. SmartPark in voltage control mode.

V. REAL-TIME SIMULATION RESULTS

In regards to wind farm and SmartParks, two different case studies are presented. In the first case study, the performance of the SmartParks to mitigate transmission line power fluctuations is presented and compared to case without SmartParks in active power control mode. In the second case study, the performance of the SmartParks in voltage control mode is compared with a STATCOM when it is connected to bus 4.

A. Case Study 1

The power flow fluctuations in transmission lines 1-6 and 6-4 caused by the variations in wind power (Fig. 5) are plotted in Figs. 6 and 7. Without an ACD controller, significant power fluctuations occur in the lines. These fluctuations may result in penalties that lead the wind farm to lose revenue. The ACD controller reduces the fluctuations in the transmission lines from the reference line power flow values and hence minimizes the deviation penalty charged to the wind power provider.

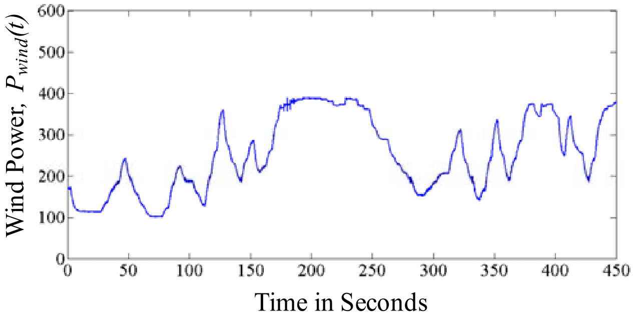

Figure 5. Wind power profile generated for simulation in RTDS.

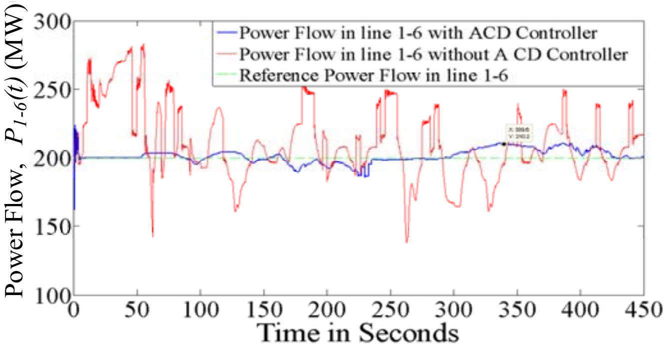

Figure 6. Comparison of power flow in transmission line 1-6 with and without ACD (α_1=1; α_2=1; α_3=1).

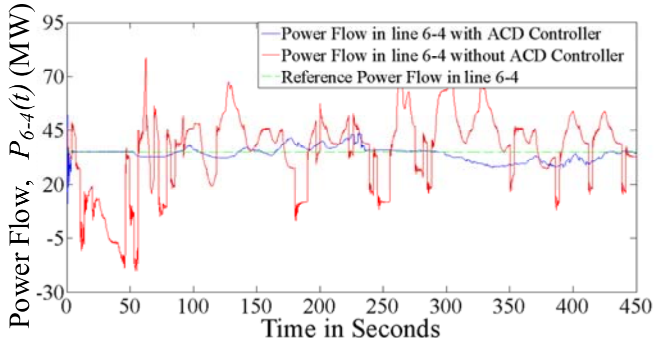

Figure 7. Comparison of power flow in transmission line 6-4 with and without ACD (α_1=1; α_2=1; α_3=1).

B. Case Study 2

An experiment was carried out to study the impact of wind speed variation on the system (Fig. 1) and to observe how the SmartParks respond to reactive power control. Initially, it is assumed that the wind speed is 10 m/s; at that speed, the wind farm generates 190 MW. At this point, the voltage at bus 4 is

0.974 p.u. without any reactive compensation. With the SmartParks in voltage control mode, that voltage can easily be regulated to 1.0 p.u. as before. Now, suddenly, the wind speed is changed from 10 m/s to 12 m/s, which changes the wind power generation to 350 MW. Without any voltage regulation, this change in wind power moves the entire system to a new operating point where the voltage at bus 4 also changes to 0.983 p.u. However, with the STATCOM or the SmartParks in voltage control mode, connected at bus 4 (Fig. 8) at both of these operating points, the voltage at bus 4 can be maintained successfully at 1.0 p.u., as shown in Fig. 9.

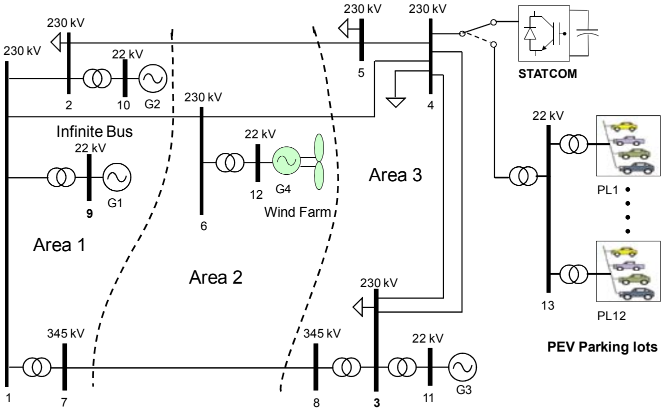

Figure 8. The 12-bus system with SmartParks/STATCOM connected at bus 4.

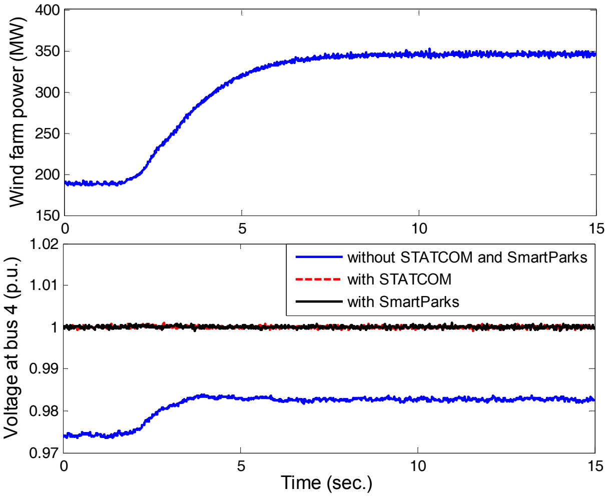

Figure 9. Performance of SmartParks during wind power changes. Comparison results are provided with a STATCOM connected at bus 4.

VI. CONCLUSIONS

Variable wind power injection in a smart grid causes power fluctuations in transmission lines connected to the wind farm bus, and voltage deviations in load buses in proximity of wind farm buses. Using SmartParks located in close proximity to a wind farm bus, optimal controllers can be developed to mitigate the active and reactive power fluctuations in a smart grid. A novel adaptive critic design approach based controller has been presented to mitigate the active power fluctuations experienced in transmission lines connected to a wind farm bus. Furthermore, SmartParks operated in voltage control mode can also provide reactive power support during wind power fluctuations and maintain selected load buses at the desired voltages.

Future research is to develop a coordinated optimal active and reactive power control strategy for SmartParks to support high levels of wind power penetration in smart grids.

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