Integration of V2H/V2G Hybrid System for Demand Response in Distribution Network

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***Abstract*- Integration of Electrical Vehicles (EVs) with power grid not only brings new challenges for load management, but also opportunities for distributed storage and generation in distribution network. With the introduction of Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G), EVs can help stabilize the operation of power grid. This paper proposed and implemented a hybrid V2H/V2G system with commercialized EVs, which is able to support both islanded AC/DC load and the power grid with one single platform. Standard industrial communication protocols are implemented for a seamless respond to remote Demand Respond (DR) signals. Simulation and implementation are carried out to validate the proposed design. Simulation and implementation results showed that the hybrid system is capable of support critical islanded DC/AC load and quickly respond to the remote DR signal for V2G within 1.5kW of power range.**

Keywords- V2G; V2H; DR; remote control

I. INTRODUCTION

The integration of Electrical Vehicles (EVs) with power grid has received tremendous attention over the last decades, partly because of the increasing market penetration of EV and its corresponding impacts on the power grid [1].

Interaction of EV with power grid consists of two separated parts: Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G). For G2V, research topics such as smart charging, charging safety and multiplexing of EV Supply Equipment (EVSE) have been extensively studied [2][3]. The idea of these studies is to understand how EV charging can be better managed so that it reaches a delicate balance between charging efficiency and impact on power grid.

On the other hand, by enabling bidirectional power flow with V2G, EV does not merely serves as a load to the grid, but also as distributed storage and generation. Researchers have long found the value of V2G in stabilizing the power grid. Examples of such applications include reactive power compensation, integration with renewable energy and voltage regulations [4]-[7]. Among these researchers, Kisacikoglu et al proposed bidirectional V2G charger architecture that utilizes the dc-link capacitor for reactive power compensation. Simulation results showed that the proposed V2G charger has better performance in harmonics and less demand in dc-link capacitors [4]. Guille et al integrated wind and solar generation with V2G. Simulation shows that large scale V2G accommodates the intermittency of renewable generation and play a significant role in distributed energy storage [5]. Lam et al studied replacing traditional voltage regulation services with V2G. Simulation was carried out to estimate the appropriate V2G capacity for regulation services [6]. Soares et al simulated a 2000 V2G in IEEE 33 bus distribution network to study the resource scheduling with particle swarm optimization [7]. However, none of the above researchers built real V2G platform for test and verification. Taking into account some unexpected problems, for example long response time, limited output power and V2G dynamics, the proposed ideas may fail to work. Therefore, it is of primary importance to design and implement a V2G capable platform.

Apart from V2G, Vehicle-to-Home (V2H) is another research area within the domain of bidirectional power flow that addresses the problem of AC load support. V2H describes a scenario that output electrical power of EV is not synchronized to the power grid, but instead it provides backup power for islanded AC load [8]. Tuttle et al simulated a household setup of photovoltaic (PV) generation and V2H, which is capable of creating an off-grid microgrid that has sufficient energy support, safety disconnects and voltage regulation [9]. Turker et al proposed a strategy targeting at minimizing the energy cost for a household taking into account the V2H and driving pattern of the EV [10]. It would be more solid if the proposed high level control strategies be tested in a cost efficient V2H platform.

Most of existing literatures on V2H and V2G verified proposed ideas with simulation, a few other literatures attempted to setup platforms which replace EVs with battery packs for verification. Ota et al are among those a few researchers who implemented an off-board charger for V2G using battery packs [11]. The work is of great pioneer value but improvements could be made on remote smart control, V2H capability, DC load support, etc. Some of the pilot V2G projects carried out in the United States use highly customized EVs [12][13]. But when implementing V2H/V2G, especially on large scale, commercialized EVs are the best candidates for such purpose. As most of the EVs on the road are commercialized models, using highly customized EVs or battery backs to verify V2H/V2G ideas cannot reveal the real difficulties sit on the road of future large scale V2H/V2G.

This paper is concerned with design and implementation of a hybrid V2H/V2G platform primarily for Demand Response (DR) in distribution network. The proposed platform aims at

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utilizing commercialized EV model as test bed. Both V2H and V2G can be performed on a single platform. Widely accepted industrial standards, i.e. CHAdeMO and SunSpec are used to achieve remote smart control of V2G. The contribution of the paper is three-fold: first, to the best of the author's knowledge, this is the first V2H/V2G system that utilizes commercialized EV and standard communication protocol, which shed light on how V2H/V2G needs to be performed on a large scale. Second, the platform has been designed to drive critical DC load, which increases the versatility of the test bed. Finally, the system is remotely controllable, allowing it to receive and respond to remote control signals. As a result, the proposed system can be used to test out a lot of ideas mentioned in the above literatures.

The remainder of this paper is organized as follows: Section II articulate the system design, in which system architecture, CHAdeMO communication, and SunSpec communication are discussed. It is followed by a simulation and prototyping. The simulation and implementation results are presented and further analyzed in the same section. Finally, conclusions are drawn in Section IV.

II. System Design

This section describes and analyzes the design of the proposed hybrid V2H/V2G system from both hardware and software aspects. It further introduced the communication protocols, i.e. CHAdeMO and SunSpec, used in the hybrid system.

A. High Level Hardware Achetecture

The design of the V2H/V2G hardware system includes the following three objectives:

- The hybrid system targets to use commercially available EV as test bed to perform V2H/V2G.
- The designed system could support critical DC load such as DC motors. It not only increases the diversity of the system, but also takes into account the real application in household scenario where some appliances are on DC.
- Remote control and can be performed and the system is able to respond to DR signals sent from an aggregator.

With these design considerations in mind, the hybrid system hardware architecture is shown in Fig. 1. Mitsubishi MiEV is chosen as the EV test bed for this test bed, because it is a popular commercialized EV model which allows DC charging/discharging through CHAdeMO port, which will be explored in further detail later. The system is a combination of both power flow and signal flow. For power flow, the electrical energy stored inside the Mitsubishi MiEV is converted to AC through a DC/AC Converter. This is the V2H part of the system. This port can drive local islanded AC load. It is followed by an AC/DC converter in the second level. The output of this level is designed to drive critical DC load. Finally, the energy goes through a grid-tie inverter and is synchronized to power grid, which is the V2G part of the hybrid system.

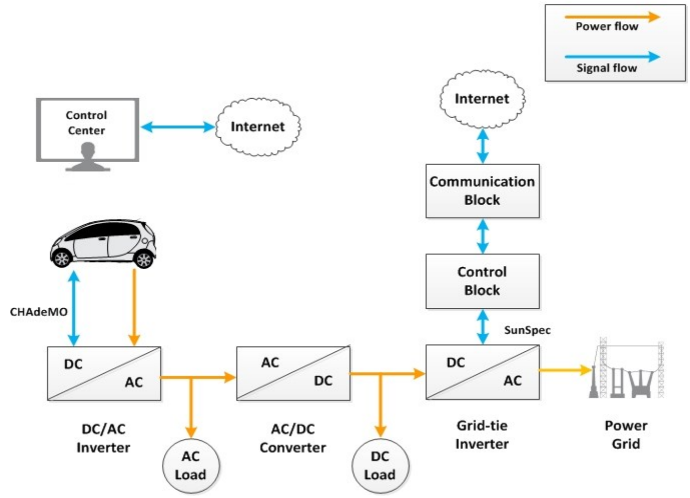

Fig. 1. Proposed V2H/V2G hybrid system hardware archetecture

Unlike power flow which is one-way, the signal flow of the system is all bidirectional. It is consists of two separated parts: information exchange between EV and the first level DC/AC inverter and control between control center and the third level DC/AC inverter. The corresponding communication protocols are CHAdeMO and SunSpec respectively. The details of the two mentioned protocols will be discussed in the following two sections.

B. High Level Software Achetecture

On software side, hierachical structure is a preffered architecture. It provides more design freedom within each level. Fig.2 shows software architecture for the same system. The software has three-layer architecture with user/aggregator layer as the upper layer, power control layer as the lower layer and application layer sits in the middle. The upper two layers are located in the control center which may have a long physical distance from the V2H/V2G hardware field. The lower power control layer is to be implemented on the hardware. The hierarchical design will provide the upper layers with interfaces and each layer may be written in different programming languages or run under different environments. The benefits of this design also allow programmers to focus on each layer rather than handling the whole design flow.

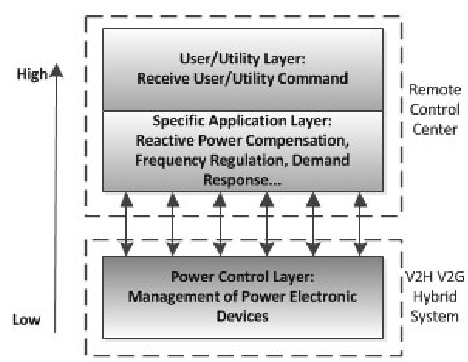

Fig. 2. Proposed V2H/V2G hybrid system software archetecture

Three layers of the system handle entirely different functions. The highest user/aggregator layer receives commands from utility and decides if V2H/V2G needs to be activated. In case multiple EVs are available for V2H/V2G, this layer will decide which EV will perform V2H/V2G based on the information of State-of-Charge (SoC), user incentives, etc. After the system decides V2H/V2G needs to be performed, the user/aggregator layer will call the functions provided by application layer. Some important applications can be performed such as reactive power compensation, frequency regulation and DR. According to the application the system chooses, it will need to adjust the output voltage profile of the last level inverter. Finally, functions in power controlled layer are called by its upper layer to change the control signals of each transistor in the circuit. On the other hand, when the system needs to read or monitor voltage or current profile of V2H/V2G, the process is still calling a function with needed return values from the highest layer.

C. CHAdeMO Communication

Communication between EVSE and EV has always been an obstacle in the implementation of V2H/V2G, which partly explains why little literature uses commercialized EV models for V2H/V2G. Before the start of discharging of battery packs on the EV, the EVSE has to communicate with EV's Battery Management System (BMS) to inform the EV batteries to discharge.

Several protocols are developed for communication between EV and EVSE, among which CHAdeMO is widely used for DC off-board fast charging [14]. The protocol standardized both hardware interfaces and data exchange format in fast charging. With the same data structure and hardware interface, CHAdeMO can be further developed and used in discharging as well. As CHAdeMO connector injects power directly to the battery packs on EV, the current bypasses the on-board single-directional inverter, making it possible of the bidirectional power flow. It is also the standard interface on the test bed setup in this paper, i.e. Mitsubishi MiEV.

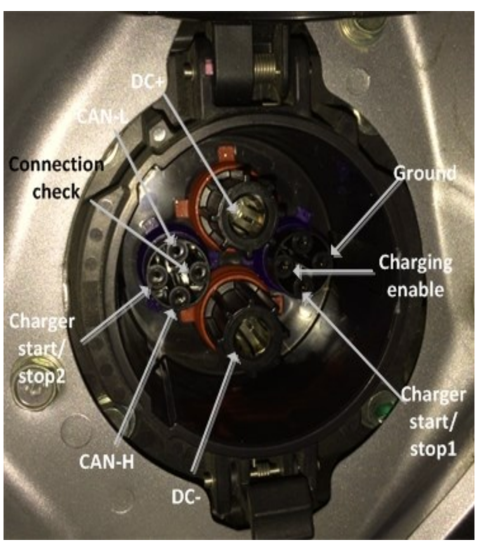

Fig. 3. Layout of CHAdeMO port on Mitsubishi MiEV

Fig. 3 shows hardware layout of a CHAdeMO connector. It has nine active connections which can be categorized into three different groups. The DC+ and DC- provide the DC link to charge and discharge the EV. CAN-H and CAN-L consist of communication channels for data exchange between EV and EVSE. On CAN bus, each data frame is transmitted every 100ms. The data frame starts with an ID indicating its functionality and followed by contents. The rest of the connections are for hand shaking and safety check before charging and discharging starts.

D. SunSpec Communication

Apart from the communication between EV and EVSE, control center and inverter need to exchange information for the purpose of remote monitor and control. The communication between the control center and inverter is implemented on an Ethernet to Modbus device with SunSpec standard.

The SunSpec standard, initially designed for PV, provides an open protocol to allow PVs, inverters, meters and environmental measurement devices to communicate on a single standard [15]. The benefits of the SunSpec standard include reduced engineering time and the need for customizations. It also results in faster deployment time and significant cost reductions, which makes SunSpec protocol optimal candidate for the proposed system.

Fig.4 illustrates how the SunSpec standard addresses the standardization of interconnected devices. There are three components in the SunSpec system: SunSpec devices, supervisory control and data acquisition (SCADA) and control center respectively. As shown in the figure, the inverter, meter, and charge controller are the SunSpec compliant devices. They communicate with SCADA through multiple physical layer protocols including but not limited to Zigbee, RS485, TCP/IP and Modbus following SunSpec standard. The SCADA serves as monitor and data logger for all SunSpec compliant devices. On the other side of the SCADA, the control center, which resides in the cloud, will perform the upper level algorithms mentioned in Fig.2 based on the information acquired by SCADA. The control commands will be sent to SunSpec devices through SCADA following SunSpec protocol.

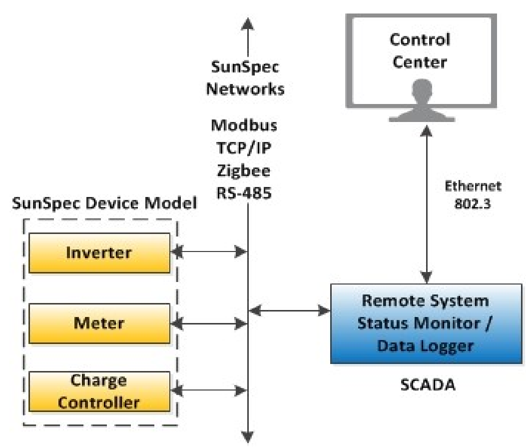

Fig. 4. SunSpec protocol archetecure

III. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation and Result Analysis

Simulation is carried out at the grid-tie inverter stage shown in Fig.1. Communication commands provide the reference value P_ref to monitor the grid-tie inverter to deliver the EV power to the Grid. A 120Vac/60Hz grid-tie inverter is modeled and simulated in Matlab/Simulink. The input voltage of the inverter is 48Vdc. Since grid-tie inverter has constant output voltage, the V2G power is adjusted by changing the inverter current. The reference value of inverter current I_ref is calculated based on the dq to abc transformation, which goes through a hysteresis controller to generate PWM signals to drive the V2G inverter. In this test, the command signal P_ref changes from 0.5kW to 0.8kW, then the inverter output current is increased from 5A to 8A accordingly, as shown in Fig.5.

B. Experiment and Results Analysis

Experimental V2H/V2G hybrid system is built based on the architecture proposed in Fig.1. Table I summarized the key parameters for the proposed test bed. The maximum power output that can be achieved by the test bed is 1.5kW. The overall efficiency and dynamic behavior will be discussed in the remainder of this section.

Fig.6 demonstrates the experiment setup of the proposed system. A Mitsubishi MiEV is served as the test bed with a rated battery voltage of 330Vac and capacity of 16kWh. As shown in the figure, it is connected with a CHAdeMO connector. The other end of the connector is connected to the DC/AC inverter. The output of the DC/AC inverter is not synchronized to the grid but is capable of supporting islanded AC load. The DC/AC inverter is cascaded with AC/DC converter with a rated output of 48Vdc. The output of the converter is able to support critical DC load. And finally, the power flow goes through a grid-tie inverter that is previously simulated in the Matlab/Simulink. A SunSpec compliant SCADA is connected with the inverter for remote control and monitor. The controller is further connected to the Ethernet and connects to the control center on the cloud. On grid side, for safety considerations, surge protectors are attached to the inverter before it is connected the grid. The rated overall power that can be extracted from the MiEV is no more than 1.5kW, which is limited by the DC/AC inverter. As shown in the figure, the proposed platform is able to perform V2H on the output of DC/AC inverter while V2G on the grid-tie inverter. The system can also support critical DC load at the output of AC/DC converter. The experimental setup can be further developed into bidirectional power flow using the J1772 port on the EV, which handles charging.

TABLE I. SPECIFICATION OF TEST BED

EV Model	Mitsubishi MiEV
Battery	330 Volt, 16 kWh
Connector Protocol	CHAdeMO
Maximum Power	1.5 kW

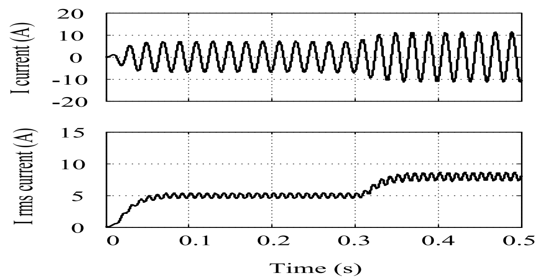

Fig. 5. Simulation result of grid-tie inverter when current RMS value changes from 5A to 8A

Two tests are run in order to validate the designed V2H/V2G hybrid system. The first test is a measurement on AC current sent to the grid under different operations. It shows the dynamics of the system or how quickly the system can respond to the remote control signal. RMS value is used to evaluate AC current. The Hall Effect sensor measures and averages out the sampled measurements over a second. Due to the limitation of the AC current sensor and the circuit noise, the accuracy is within ±0.1A. The second test is on DC. The DC test measures the DC current on the output of the AC/DC converter when the system is driving a critical DC load while performing V2G. The DC test intends to show the robustness of the designed system as the system is under different operations. The measurement on DC test is sampled at 2.5GHz. It inevitably introduces environmental noise into the system. Therefore, a first order filter will be used to filter out the measurement noise.

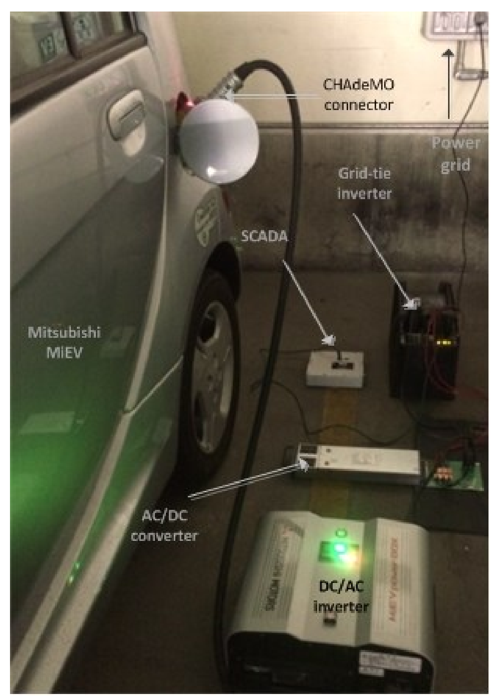

Fig. 6. Experimental setup of V2H/V2G hybrid system

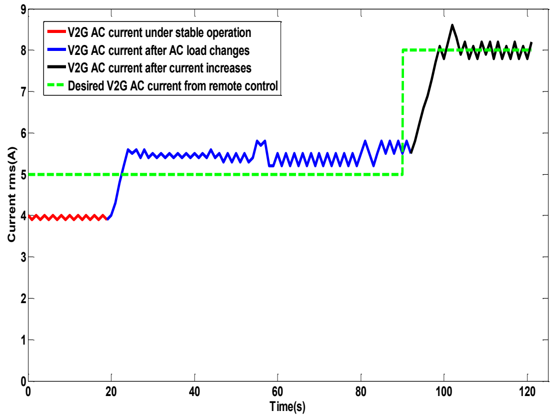

Fig. 7. Transient state of AC load changes and V2G current increases

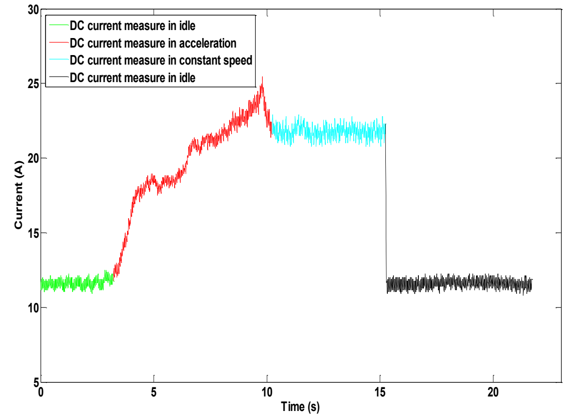

Fig. 8. Transcient state of DC load change with constant V2G power

Fig.7 presents the transient state of AC current in RMS value when the system is under different operations. The measurement is performed at the output of grid-tie inverter. The grid-tie inverter is remotely monitored and controlled. The remote control current is initially set to 5A and later increased to 8A. As shown in the figure, under initial stable operation, the output current of the grid-tie inverter is at 4A though the intended V2G current is set to 5A. The 1A difference results from two facts: first of all, V2G can be only performed within local distribution network. The power sent back to the power grid cannot transmit back to the transmission network. The power cannot go through circuit panel, not to mention most of transformers prevent bidirectional power flow. Secondly, distribution network has impedance and resistance at comparable level. The inverter changes it voltage amplitude and phase angle to inject current into the power grid. When there is not enough consumption in the local distribution grid, the voltage in the distribution grid stays at the nominal voltage. The V2G grid-tie inverter has to elevate its output voltage in order to inject the desired current, which reaches the upper limit of the output voltage for the V2G grid-tie inverter. Therefore, at the initial stable operation, there is a 1A difference between the desired value and measured value.

After operating in stable stage, the authors increase the AC load in the local distribution grid by turning on heavy duty heater for more than 2kW. The grid voltage drops because of insufficient power supply and consequently the difference between V2G grid-tie inverter and grid voltage become larger. As expected, the output current of the V2G grid-tie inverter reaches the desired value of the current. It operates in stable state for around 75s. The zigzag current is due to sensor inaccuracy as well as slight load change from the distribution network. As load changes, the closed-loop inverter always maintains it output at 5A. The error between desired and measured current is within a reasonable tolerance range.

In the last part of this experiment, a DR signal to increase the current from 5A to 8A is sent to the inverter through SCADA. As shown in Fig.7, hybrid system responds to the command and increases its current to 8A. The experiment results verify the simulation performed earlier in Matlab/Simulink which is shown in Fig. 5.

After the experiment on AC transient state, experiment on DC side is also carried out to demonstrate the flexibility and versatility of the designed V2H/V2G system. At the output of AC/DC converter a critical DC load is connected to the system. In this paper, a brush permanent magnetic DC motor with a rated voltage of 12-72Vdc is used as the critical load. The instant DC current is measured at the output of the DC/AC inverter where the nominal voltage is 48Vdc.

Fig.8 shows the DC transient state under different operations of the DC motor when V2G is performed for 5A on the grid-tie inverter side. The initial current is around 11A when motor is first in idle state. Then the motor is accelerated, the current reaches a maximum of 25A. After reaching its maximum speed, it falls into the constant speed state where the current measurement is around 22A. For the whole process, the V2G is working on 5A on grid-tie inverter side. And finally the motor falls back to idle stage where the 11A current reflects the constant V2G on grid side. This experiment demonstrates the robustness and versatility of the designed system. It is able to support critical DC load while maintaining constant power of V2G.

The above two experiments demonstrate the preciseness of the designed system. If V2H and V2G combined are performed in 1.5kW range continuously, with a battery capacity of 16kWh, i.e. the capacity of Mitsubishi MiEV battery, it can achieve continuous V2H/V2G for more than 10 hours. However, it should be noted that the flexibility and versatility is at the expense of system level efficiency. According to the measurement, 1.3kW power deliveries at V2H stage is only measured at 1.06kW at the output of V2G stage, having an efficiency of 81.5%.

IV. CONCLUSIONS

This paper has proposed a V2H/V2G hybrid system that can be remotely controlled and monitored. The commercialized EV model, Mitsubishi MiEV, is utilized as test bed. Widely used CHAdeMO protocol is chosen for communication between EV and EVSE. For communication between SCADA and inverter, SunSpec is implemented as the communication protocol. Experimental results show that the proposed system supports both islanded DC/AC load as well as the power grid.

The hybrid system can respond to remote DR signal and respond to it within 1.5kW range. AC and DC test are performed to study the dynamics and robustness of the proposed system. Experiments also indicate that V2G can only be performed in local distribution network and the performance of V2G depends heavily upon the load profile of the distribution network.

Research following this proposed V2H/V2G system should include two subjects of interest: on V2H/V2G hardware side, improvement is needed to extend the maximum V2H/V2G power and increase its efficiency. More effort is to be put on bidirectional power flow using CHAdeMO port on the same EV. On software side, reactive power compensation and voltage regulation will be evaluated and tested to show how the existing platform can contribute to these applications.

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