Starlink Space Network-Enhanced Cyber–Physical Power System

Tong Duan, *Graduate Student Member, IEEE*, and Venkata Dinavahi, *Fellow, IEEE*

***Abstract*—The information and communication technology (ICT) is increasingly involved in the measurement, operation, control and protection of the cyber-physical power system (CPPS). As one of the most promising communication infrastructure projects, Starlink is a satellite Internet constellation being constructed by SpaceX for providing global Internet access, which can benefit the network service supply for the communication-enabled power system equipment in locations where the network access is unreliable, expensive, or completely unavailable. In this letter, the future applications of the Starlink space network in CPPSs are explored: the communication infrastructure and transmission parameters are discussed, and the corresponding test case was emulated in real-time on the heterogeneous co-emulation platform to validate the proposed concept of space network enhanced cyber-physical power system.**

***Index Terms*—Communication network, co-simulation, cyber-physical power system, free space, Internet, power system simulation, space network, Starlink.**

I. Introduction

WITH new developments in information and communication technologies (ICTs) and communication-enabled power equipment, the cyber-physical power system (CPPS) is gradually maturing due to the ICT-enabled real-time measurement, dynamic operation and smart control. Applying ICTs to power systems not only requires the upgrade of communication modules installed on the various power equipment such as power electronics converters [1], but also relies on the communication network infrastructure that can provide fast and stable connection between networking devices even at remote locations. However, the network service is not always reliable in many places such as rural areas and offshore fields, or could even be completely unavailable during severe environmental conditions such as the hurricanes and earthquakes, which makes the stable measurement and smart operation of CPPSs in these places difficult.

To provide the globally connected Internet service, SpaceX began the satellite constellation project, called Starlink, in 2015. The first two prototype test-flight satellites were launched in February 2018. Up to now, SpaceX has launched nearly 800 satellites [2]. Although it is still at the very initial stage of the entire project, the final Starlink space network will be composed of nearly 12,000 satellites (with a possible extension to 43000 satellites) when it is completed, where each satellite will circle the Earth at an orbit of 500 km to 1200 km overhead. As illustrated in Fig. 1, the numerous satellites could potentially provide all time Internet services with global coverage from relatively low orbits. Despite the extra cost of installing new communication antennas, the space-Internet could achieve even lower transmission latencies than the existing terrestrial fiber networks for long distances [3], [4]. Although there are still many technological challenges to overcome [5], it may forever change the landscape of the telecom industry if the project could be successfully completed.

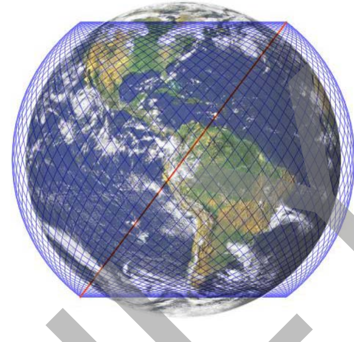

Fig. 1. Demonstration of the Starlink initial phase: 1584 satellites into 72 orbital planes [2].

Since Starlink is based on the space wireless transmission in a low orbit without suffering from service quality problems in remote places or under abnormal conditions, it could expose massive potentials in the industrial application of cyber-physical power systems, although the project is still under construction. In this letter, the concept of Starlink space network enhanced CPPS is proposed: the Starlink transmission parameters are first investigated to exploit the capability of space data transmission; then the system structure and implementation techniques are discussed to look into the future applications; finally, the advantages of the proposed concept of space network enhanced cyber-physical power system is demonstrated in the IEEE 39-bus test power system based case study.

II. Space-Network Enhanced Power System Structure and Implementation

In CPPSs, the real-time measurement and control are achieved via the data packet based connection between the communication modules installed on various power equipment. The transmission can be wired in fiber or wireless in vacuum, as long as the transmission latency could meet the performance requirements and the economic cost is reasonable. Fortunately, due to the low orbit (550 km altitude) and fast transmission speed in vacuum, the propagation delay difference between the SpaceX's Phase I Starlink constellation and the terrestrial optical fiber network is small, and the delay of space propagation could be even smaller when the hop distance is longer than 2500 km [3]. Therefore, the Starlink

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The authors are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2V4, Canada (e-mail: tduan@ualberta.ca; dinavahi@ualberta.ca).

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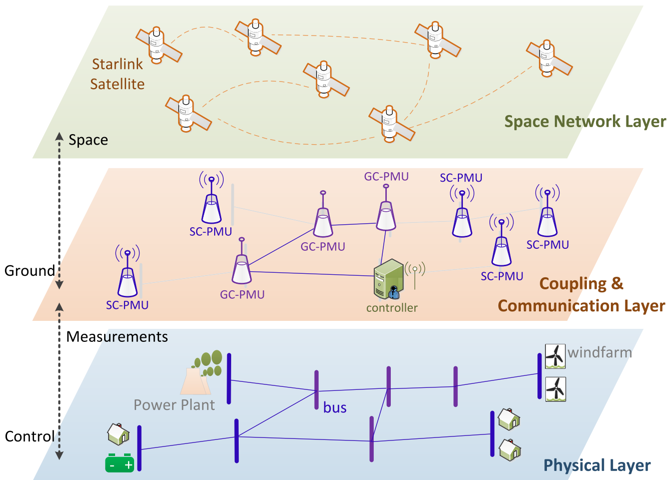

Fig. 2. Proposed space network enhanced cyber-physical power system architecture.

network could be exploited in the CPPS for wide area measurement, protection and control (WAMPAC) applications in the areas with weak network connections. The proposed space network enhanced cyber-physical power system is shown in Fig. 2, where the space network layer is added to the existing two-layer CPPS architecture.

The physical layer contains the power generation, distribution, transmission, storage, conversion, consumption, and protection equipment, where the renewable energies such as the windfarm generation and solar power generation are also included in the system. The basic network component in the cyber layer (coupling and communication layer in Fig. 2) is the sampling and reporting device installed on the power equipment or processing buses, and the commonly used device is the phasor measurement unit (PMU) [6]. A PMU is responsible to measure the electrical quantities and report the corresponding phasor values to the phasor data concentrator (PDC) that collects the measurements from the PMUs in the area or the controller that makes decisions for global control. In addition to the traditional physical and cyber layers, the third layer - space network layer, is proposed in this letter.

The space network layer is utilized to provide fast and reliable connection services for the areas where the ground based network service is not good. As shown in Fig. 2, assume that some PMUs (called space communication based PMU, SC-PMU) are located at higher elevations or offshore places and no stable links can be connected, which are different from the traditional ground communication based PMUs (GC-PMU). Then their operations (including reporting measurement data to PDCs and controllers and receiving control policies from the controller) is based on the space communication between the PMUs, PDCs and controllers. As estimated by [3], the transmission delay for a 5000 km distance could be smaller than 20ms, which is quite significant to meet the delay requirements of PMU connections. In fact, the time requirement of the phasor measurement based detection and control action is on the order of 200-300ms [7], and the transmission delays are insignificant to impact the overall operation time of wide-area control scheme. Therefore, it can be expected that the global power system measurement and control can be achieved with the space network layer involved in the cyber layer.

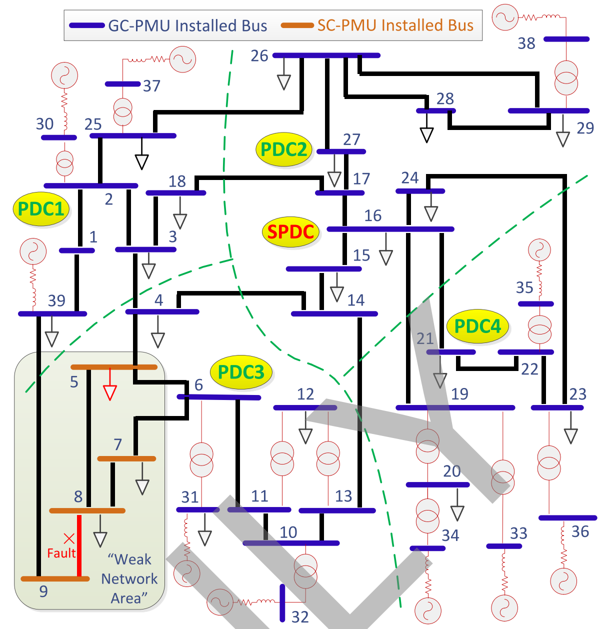

Fig. 3. IEEE 39-bus test power system and cyber-layer configuration.

For the implementation of the Starlink space network enhanced cyber physical power system, SC-PMU is the key component since the construction of space network is the task of Starlink. The SC-PMU can be customized by installing a user terminal to enable the space data transmission via the satellites: according to [2], the size of the flat user terminal is like a pizza box, which has phased array antennas and can track the satellites. The terminals can be mounted anywhere, as long as they can see the sky. With the technology development and mass production, the terminal price can be very low. Another implementation issue is the communication protocols, since it is not practical and economical to customize the Starlink satellites for pure CPPS applications. Fortunately, except for the local communication networks within a substation where the protocols are customized based on MAC address, in wide area communication of CPPS the transmission standards such as the IEC 61850 [8] are all based on the IP address, which means the CPPS communication network can directly use the Starlink Internet service for its own applications.

III. Evaluation on Real-Time Heterogenous Co-Emulation Platform

Since the Starlink system is still under construction, the advantages of the proposed future CPPS blueprint can only be validated via co-simulation approaches [9]. In this work, the IEEE 39-bus test power system [10] was emulated on the heterogeneous Jetson-FPGA co-emulation platform [11]. The test system is shown in Fig. 3, where each bus is assumed to have a GC-PMU or SC-PMU installed and each transmission line connecting two GC-PMUs is assumed to have a communication link in cyber layer. The system is partitioned into four areas with four PDCs installed at buses 2, 6, 21, 27 [9]. The system-level control center is located at Bus-16, called the super PDC (SPDC).

The terrestrial transmission delay of each communication fiber link in the simulator is set at 1ms/200km; and the forwarding rate of each PMU is set at 100Mbit/s. Assume the area

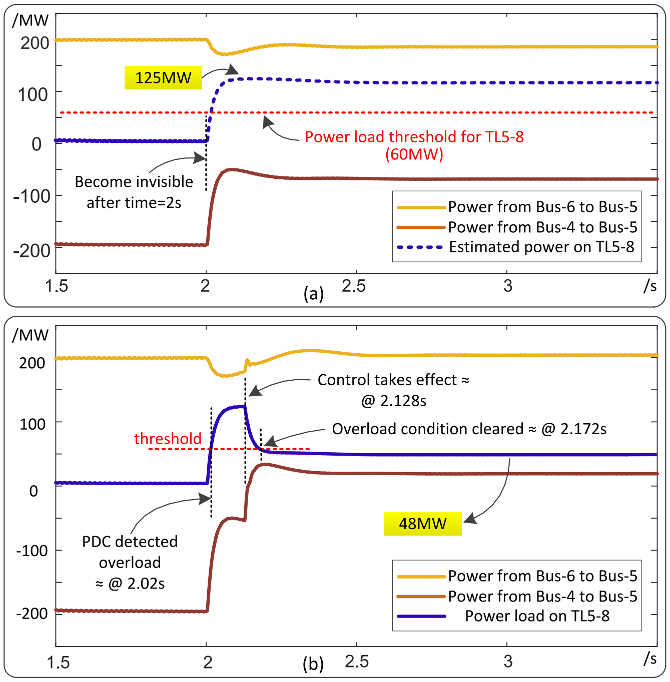

Fig. 4. Emulation results of active power flows in the two cases: a) ground-based networking; b) space based communication case.

(called "weak network area" in this work) containing buses 5, 7, 8, and 9 is in poor network quality and thus the SC-PMUs are installed to leverage the Starlink space network service to connect with PDC3. Since the distance between the SC-PMUs and PDC3 is smaller than the one hop distance (659 km) of the space satellite transmission, the transmission delay between the SC-PMUs and PDC3 is set at 6ms [3]. In this test case, assume that a fault occurred on the line between Bus-8 and Bus-9 (TL8-9) at time 2s, which resulted in the trip operations of the protection relays at the two ends. The outage of the line leads to the overload of the line between Bus-5 and Bus-8 (TL5-8), which can be relieved by controllable loads at Bus-5 as the remedial action scheme (RAS). The active power load threshold for TL5-8 is set at 60MW.

The simulation results compared two cases: ground-based networking and space communication based networking in the weak network area. In the ground-based networking case, assume that the communication service in the weak network area broke down from time 2s to 20s due to some unexpected severe environmental conditions. As shown in the active power flows in Fig. 4(a), the load on line TL5-8 could not be observed by PDC3 after 2s and the overload fault was not cleared by the control center. Although the load on line TL5-8 can be estimated (denoted as the blue dot line) based on the power flowing through line TL4-5 and TL6-5 from the measurements of Bus-4 and Bus-6, the control command could also not be sent to the controllable load on Bus-5 to relieve the power due to the unavailable network service. Therefore, the transmission line TL5-8 kept working with overload, which may result in unnecessary line outages.

In the space based communication case, the network service is always accessible since the environmental conditions do not influence the space networking. As shown in the results in Fig. 4(b), PDC3 detected the overload fault quickly and the controller could respond to the abnormal condition with a low delay. After the load adaption command was sent to the controllable load at Bus-5, the load on line TL5-8 was reduced to a safe amount and a large outage could be avoided. The total 108ms response delay is composed of the 19ms round transmission delay, 39ms analysis and decision making delay, and 50ms controllable load action delay, which is small enough for the system-level remedial protection. In addition, the transmission between the SC-PMUs and PDC3 only requires one hop due to the large terrestrial distance cover range of one satellite. In fact, a single satellite is able to cover most areas in this test system scale. This simple test case demonstrates that the Starlink space network layer can be leveraged to enhance the connection quality of the existing CPPS architecture.

IV. Conclusion

In this letter, the possibility of integrating the Starlink space network into the existing CPPS is explored. The three-layer CPPS architecture is first proposed and then implementation issues are discussed. Based on the communication infrastructure and transmission parameters, and the corresponding test case was emulated on the heterogeneous co-emulation platform to validate the advantages of the proposed concept. The emulation results show that the Starlink space network could be complementary to the existing communication network infrastructure. It is expected that such a space network can be utilized for wide-area control and protection of large-scale power systems and can be efficacious in improving system stability and reliability. More practical test cases including the cyber-attacks [12] and hybrid AC/DC grids will be considered based on the proposed space network enhanced cyber-physical power system.

References

[1] R. Burgos and J. Sun, "The future of control and communication: Power electronics-enabled power grids," *IEEE Power Electron. Mag.*, vol. 7, no. 2, pp. 34–36, Jun. 2020.

[2] *Starlink—Wikipedia*. Accessed: Sep. 10, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Starlink

[3] A. U. Chaudhry and H. Yanikomeroglu, "Free space optics for next-generation satellite networks," *IEEE Consum. Electron. Mag.*, early access, Oct. 9, 2020, doi: 10.1109/MCE.2020.3029772.

[4] A. I. A. Ghafar, Á. V. Castro, and M. E. Khedr, "Satellite IoT services using multichord peer to peer networking," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, Sep. 2019, pp. 566–571.

[5] J. Foust, "SpaceX's space-Internet woes: Despite technical glitches, the company plans to launch the first of nearly 12,000 satellites in 2019," *IEEE Spectr.*, vol. 56, no. 1, pp. 50–51, Jan. 2019.

[6] M. Adamiak, B. Kasztenny, and W. Premerlani, "Synchrophasors: Definition, measurement, and application," *presented at the 59th Annu. Georgia Tech Protective Relaying*, Atlanta, GA, USA, Apr. 2005, pp. 57–62.

[7] C. Martinez, M. Parashar, J. Dyer, and J. Coroas, "Phasor data requirements for real time wide-area monitoring, control and protection applications," EIPP Real Time Task Team, Chennai, India, White Paper, Jan. 2005.

[8] "Communication networks and systems for power utility automation—Part 1: Introduction and overview," IEC, Geneva, Switzerland, IEC Rep. TR 61850-1:2013, 2013.

[9] S. C. Müller *et al.*, "Interfacing power system and ICT simulators: Challenges, state-of-the-art, and case studies," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 14–24, Jan. 2018.

[10] *PSCAD^{TM} IEEE 39 Bus System, Reversion 1*, Manitoba HVDC Res. Centre, Winnipeg, MB, Canada, 2010.

[11] T. Duan, T. Cheng, and V. Dinavahi, "Heterogeneous real-time co-emulation for communication-enabled global control of AC/DC grid integrated with renewable energy," *IEEE Open J. Ind. Electron. Soc.*, vol. 1, pp. 261–270, Sep. 2020.

[12] A. A. Jahromi, A. Kemmeugne, D. Kundur, and A. Haddadi, "Cyber-physical attacks targeting communication-assisted protection schemes," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 440–450, Jan. 2020.