Impact of Simultaneous Activities on Frequency Fluctuations: Comprehensive Analyses Based on Real Measurement Data from the FNET/GridEye

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***Abstract*—Simultaneous human activities, such as the Super Bowl game, would cause certain impacts on frequency fluctuations in power systems. With the help of FNET/GridEye measurements, this paper aims to give comprehensive analyses on the frequency fluctuations during Super Bowl LIV held on Feb. 2, 2020, so as to better understand several phenomena caused by simultaneous activities which will help system operations and controls. First, recent developments of the FNET/GridEye are briefly introduced. Second, the frequency fluctuations of the Eastern Interconnection (EI), western electricity coordinating council (WECC), and electric reliability council of Texas (ERCOT) power systems during Super Bowl LIV are analyzed. Third, frequency fluctuations of Super Bowl Sunday and ordinary Sundays in 2020 are compared. Finally, the differences of frequency fluctuations among different years during the Super Bowl and their change trends are also given. Furthermore, several possible explanations, including the simultaneity of electricity consumption at the beginning of commercial breaks and the halftime show, the increasing usage of the Internet, and the increasing size of TV screens, are illustrated in detail in this paper.**

***Index Terms*—Frequency fluctuation, FNET/GridEye, simultaneous activities, Super Bowl, synchrophasor measurement.**

I. INTRODUCTION

THE power generation and consumption in power systems varyies constantly, so the system frequency is also fluctuating with the change of power balance and the operation points [1]–[3]. Typically, the frequency fluctuations are random and irregular. However, in some synchronized festival activities, a relationship is observed between human activities and frequency fluctuations. Therefore, it is interesting and meaningful to analyze the frequency fluctuations during festival activities, compare them with frequency fluctuations on ordinary days, and explore the possible causes of these phenomena.

A few relevant studies have emerged in recent years. In [4], the relationship between frequency fluctuations and simultaneous human activities is first discussed based on the data recorded by a frequency monitoring network (FNET) during Super Bowl XLII (held in 2008) in the Eastern Interconnection (EI) power system, which reveals the correlations between the frequencies in power systems and those occuring during the game. In [5], the 2010 International Federation of Association Football (FIFA) World Cup, which is a men's soccer competition held in Germany, is used to analyze the societal event impacts on the frequency fluctuations in the German power system. During the semi-final match between Germany (i.e., host country) and Spain, 31 million Germans watched the soccer game at the same time and large frequency fluctuations were observed in the halftime break and when Spain scored a goal in the 73rd minute. The frequency fluctuations during Super Bowl XLIV (held in 2010) and an online survey about viewers' activities during commercial breaks, halftime breaks and after touch-downs were also performed to determine the reasons for such phenomena. In [6], impacts of synchronized human activities on frequencies in power systems are further analyzed via the data collected by FNET during Super Bowl XLVII (held in 2013), and the data in EI, western electricity coordinating council (WECC) and electric reliability council of Texas (ERCOT) power systems are all studied together. Five observations are reported in [7], i.e., 1) Many frequency events occurred during broadcasting time; 2) Frequency events were more likely to happen during commercial breaks; 3) Large frequency fluctuation happened during the halftime break; 4) A sharp drop of frequency occurred at the beginning of the halftime break; 5) All U.S. interconnection systems (EI, WECC and ERCOT) oscillated during large frequency disturbances. In [8], the frequency fluctuations during Super Bowl XLVII, XLVIII and L (held in 2013, 2014 and 2016) are

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analyzed together for comparisons, and the authors speculate that the display brightness of watches is one of the essential factors for frequency fluctuations and the development of display technologies may impact frequency fluctuations of future Super Bowls.

Given this background, this paper aims to perform comprehensive analyses for the impact of simultaneous activities on frequency fluctuations based on real measurement data from the FNET/GridEye and use Super Bowl Sundays as examples. The purposes and contributions of this paper can be summarized as follows.

1) This paper introduces the recent development and structure of FNET/GridEye, and provides the latest data about the observed frequency fluctuations in the U.S. power system during Super Bowl LIV (held in 2020). The data utilized are more accurate and abundant compared with our previous study.

2) Comprehensive analyses are performed for the frequency fluctuation, and detailed comparisons with frequency fluctuations during the previous Super Bowl Sundays and future trends are given as well through statistical studies. Compared with our previous study, more potential reasons for identified phenomena, such as the changing system structure, higher penetration of renewable energy sources, larger size of TV screens, and more viewers on the Internet, are presented for reference.

3) The theoretical causes of frequency fluctuations and corresponding control measures for different scenarios are introduced. In addition, these control measures are discussed more specifically for the frequency fluctuations during Super Bowl Sunday.

The rest of this paper is organized as follows: Section II introduces the architecture and development of the FNET/GridEye which is the basis of frequency data collection. Section III analyzes the frequency events and fluctuations during Super Bowl LIV. Section IV provides comparisons about the differences of frequency fluctuations between Super Bowl LIV and previous ones, followed by a prediction of the future trend. Section V discusses the theoretical causes of frequency fluctuations and the corresponding control measures. Section VI provides our conclusions.

II. ARCHITECTURE AND RECENT DEVELOPMENT OF FNET/GRIDEYE

FNET/GridEye is a wide-area monitoring system aiming to enhance the situation awareness capability in power systems [9], [10]. FNET/GridEye is composed of three parts, i.e., deployed frequency disturbance recorders (FDRs), data communication network, and the FNET/GridEye server hosted at the University of Tennessee (UTK). The overall architecture of the FNET/GridEye is shown in Fig. 1 and the deployment of FDRs in the United States are shown in Fig. 2, respectively [11], [12]. First, frequency, voltage amplitude and phase angle data are sampled by FDRs; then, these measurements are sent through the public Internet with TCP/IP protocols and routers while the firewall is utilized to deny unauthorized access; finally, measurements are saved in the database and the backup server, while the website server and the application server are employed for various useful real-time and off-line applications.

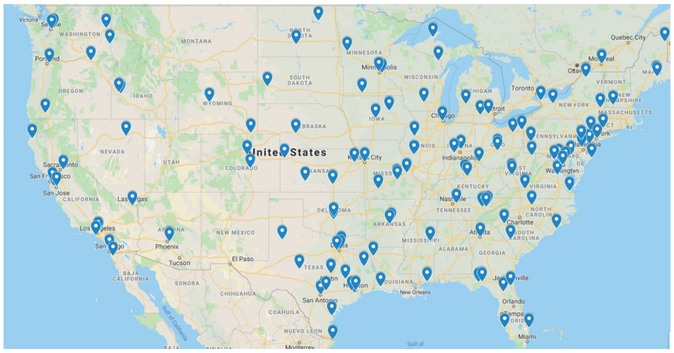


Fig. 2. Locations of FDRs in the United States (Source: http://fnetpublic.utk.edu/images/FDRDeployment.png).

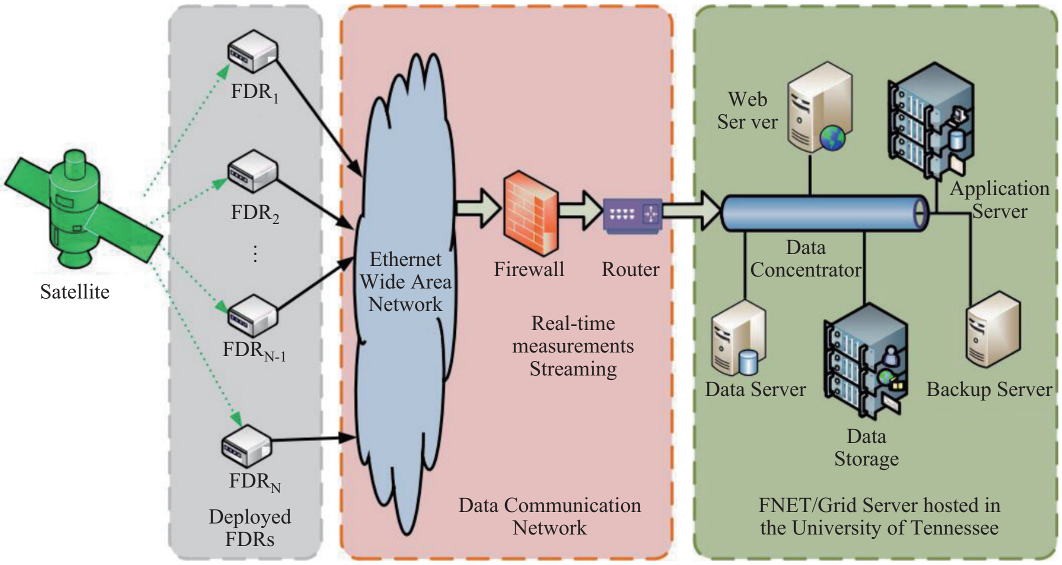


Fig. 1. Architecture of FNET/GridEye.

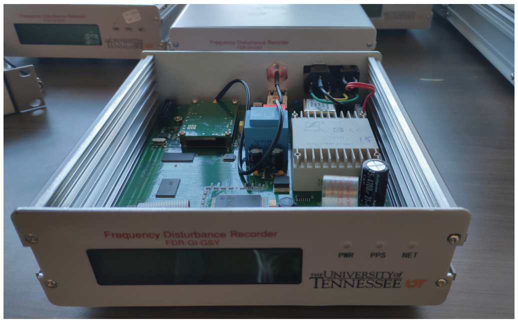


Fig. 3. Frequency disturbance recorder.

A typical FDR is shown in Fig. 3, which consists of the global position system (GPS) signal receiver module, power supply module, voltage transducer module, analog-to-digital (A/D) sampling module, digital signal processing (DSP) module, and communication module [12]. So far, more than 300 FDRs have been deployed across the world and they can achieve very high accuracy with less than 0.00006 Hz or 0.005° absolute error with respect to frequency or phase angle measurements [13]. Compared with phasor measurement units (PMUs), FDRs are much cheaper, and more effective phase angle and frequency sampling algorithms are employed for FDRs to improve their accuracy. In our previous study [14], it was demonstrated that FDRs can achieve higher accuracy than PMUs with regard to phase angle and frequency measurements.

Currently, most FDRs deployed are able to record frequency, voltage amplitude and phase angle measurement with a 10 Hz reporting rate. Furthermore, the universal grid analyzer (UGA), i.e., the updated version of FDR, has been recently developed, and can achieve up to a 1.44 kHz reporting rate [15], [16], which is even much higher than commercial PMUs although it also requires high hardware performance and communication ability, and is not widely deployed. Several studies, including event detection and location, animations for frequency and angle perturbations, oscillation detection, islanding detection, and power system instability prediction have been performed based on FNET/GridEye and achieved quite good results [17], [18]. FNET/GridEye can also provide powerful support for analyzing the frequency fluctuations during simultaneous festival activities.

It should be clarified that the data utilized in this study are collected by FDRs with a 10 Hz reporting rate, since the UGAs with 1.44 kHz have not been widely deployed; and there is no need to use such a high reporting rate to analyze the system frequency fluctuations.

III. ANALYSIS OF FREQUENCY FLUCTUATIONS DURING SUPER BOWL LIV

The Super Bowl is an annual championship game of the National Football League (NFL) and there are also big celebration events for the game. The Super Bowl is usually held on the last Sunday of January or the first Sunday of February, which is called Super Bowl Sunday. For years, the Super Bowl was the most-watched TV show in the United States, and it gradually has become an unofficial national holiday. The latest Super Bowl game (i.e., Super Bowl LIV) was held on February 2nd 2020 in Miami with 102 million TV viewers. As shown in Table I, Super Bowl LIV began at 18:14:49 and ended at 22:10:42, and there were 22 commercial breaks (about 2.5 min for each) and 1 halftime show (about 25 min) during the game.

Some viewers might simultaneously use restrooms, open refrigerators, use computers, or use stoves during the breaks and show [5]. Therefore, there would be frequency fluctuations in power systems recorded by the FNET/GridEye. It should be mentioned that the time zone associated with the Super Bowl refers to the Eastern Standard Time (EST). During Super Bowl LIV, 8 events, including load shedding (LS) and generation trip (GT) were detected and recorded by FNET/GridEye in total, and there were 7 and 1 of them detected in EI and WECC power systems, respectively. The frequency data of EI and WECC power systems are respectively shown in Figs. 4 and 5. In addition, the time periods of commercial breaks and the halftime show, and the exact event-detection times, the types and the duration of each event, are also given.

In general, the frequency of a given regional power system is the same and synchronous regardless if we measure it in distribution networks or transmission networks [19]. Therefore,

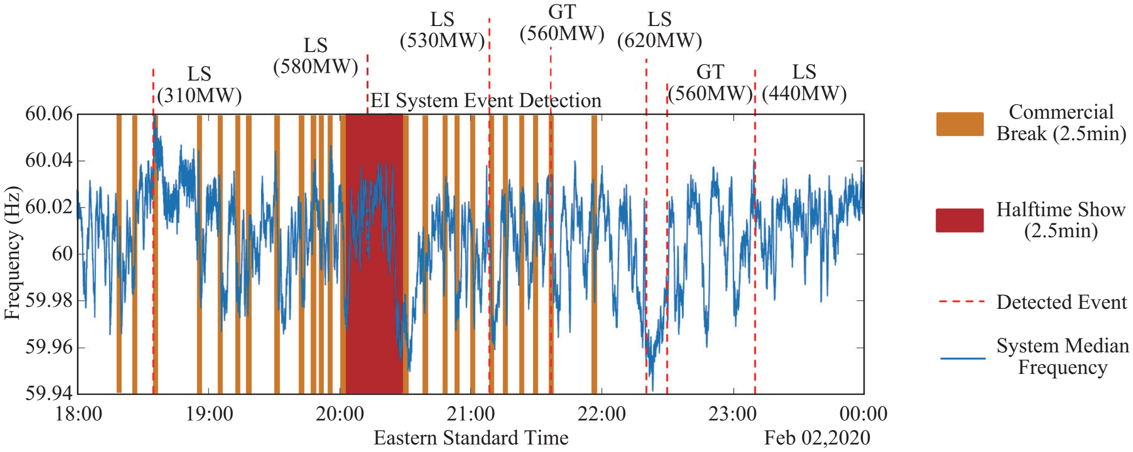


Fig. 4. Frequency fluctuations and events detected in the EI power system during Super Bowl LIV.

TABLE I
TIME PERIODS OF COMMERCIAL BREAKS AND HALFTIME SHOW DURING SUPER BOWL LIV

18:14:49 Begin	18:20:54 ∼ 18:22:52	18:28:40 ∼ 18:31:30	18:35:04 ∼ 18:39:20
18:53:10 ∼ 18:56:00	19:05:32 ∼ 19:08:01	19:11:30 ∼ 19:14:00	19:15:57 ∼ 19:18:32
19:20:20 ∼ 19:22:41	19:30:27 ∼ 19:32:58	19:39:34 ∼ 19:42:03	19:46:36 ∼ 19:49:08
19:51:27 ∼ 19:53:58	19:55:33 ∼ 19:58:15	20:01:04 ∼ 20:03:53	*20:03:54 ∼ 20:28:00*
20:28:01 ∼ 20:30:29	20:35:33 ∼ 20:37:59	20:42:40 ∼ 20:45:15	20:51:15 ∼ 20:53:40
20:59:13 ∼ 21:01:44	21:06:50 ∼ 21:09:29	21:14:03 ∼ 21:16:50	21:22:14 ∼ 21:24:46,
21:28:52 ∼ 21:31:13	21:35:40 ∼ 21:38:20	21:53:27 ∼ 21:55:43	**22:10:42 End**

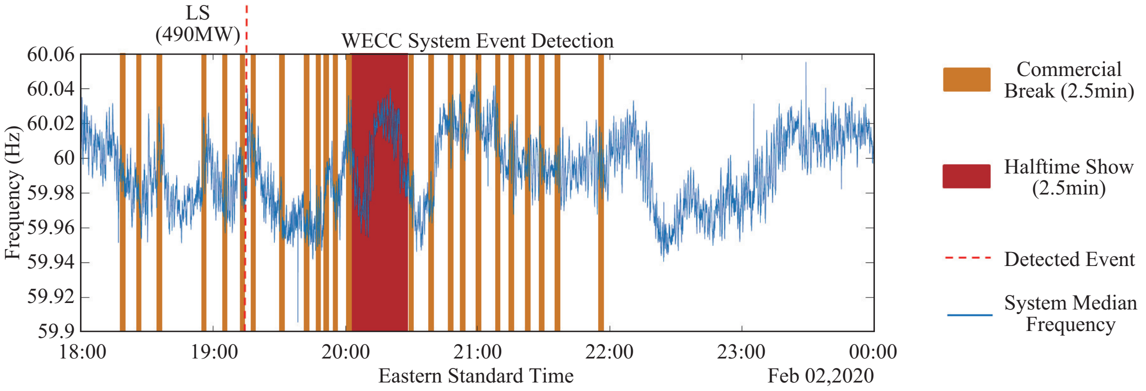


Fig. 5. Frequency fluctuations and events detected in the WECC power system during Super Bowl LIV.

the frequency measured by FDRs in distribution networks can also be viewed as the frequency of transmission networks. Therefore, on the one hand, the frequency data measured by FDRs are quite accurate, at least in their local places; on the other hand, the wide deployment of FDRs and the concept of “system medium frequency” can help to determine the typical frequency of a given power system.

Since large numbers of FDRs are deployed in EI or WECC power systems, there will be several different measured values of frequency data for one power system. To use a typical value to represent the system frequency and avoid the influence of bad data and null data, the system median frequency is utilized in this study. Assume that there are M FDRs deployed in a given power system, then the system median frequency at time t can be determined by using the median value of the M measured frequency at time t as:

$$f_t = \begin{cases} f^{\mathrm{R}}_{\frac{M+1}{2},t} & \text{if } M \text{ is odd number} \\ \frac{1}{2}\left(f^{\mathrm{R}}_{\frac{M}{2},t} + f^{\mathrm{R}}_{\frac{M}{2}+1,t}\right) & \text{if } M \text{ is even number} \end{cases} \tag{1}$$

where f_t is the system median frequency at time t; $f^{\mathrm{R}}_{\frac{M+1}{2},t}$, $f^{\mathrm{R}}_{\frac{M}{2},t}$ and $f^{\mathrm{R}}_{\frac{M}{2}+1,t}$ denote the $[(M+1)/2]^{\mathrm{th}}$, $(M/2)^{\mathrm{th}}$ and $(M/2+1)^{\mathrm{th}}$ values of the ranked frequency data at time t, respectively.

For the EI power system, it can be seen that 5 load shedding events with totals of 310 MW, 580 MW, 530 MW, 620 MW and 440 MW are detected at 18:35:10, 20:09:51, 21:07:09, 22:19:10 and 23:09:22 respectively; and 2 generator trip events with both totaling 560 MW are detected at 21:37:46 and 22:35:04, respectively. For the WECC power system, a load shedding event with a total of 490 MW is detected at 19:15:16. It can be seen from Figs. 4 and 5 that all the 5 events during the Super Bowl in EI and WECC are associated with commercial breaks or the halftime show, which indicates the simultaneous activities during these time periods could influence frequency fluctuations. In addition, sharp frequency drops can be seen at the beginnings of almost all commercial breaks and the halftime show, and the sharpest drop occurs during the halftime show. The reasons could be explained as i) Many Super Bowl viewers tend to use additional electrical household appliances, such as stoves, microwave ovens or conventional ovens during commercial breaks and the halftime show but do not turn off the TV, and these activities are almost simultaneous since people are more likely to start using them once a break begins. ii) These electrical household appliances would add a large amount of load to power systems. For example, assuming 800 W for each microwave oven and 1% of the people used it during commercial breaks, more than a 800 MW load would be added into the power systems, which would definitely result in observable frequency fluctuations. iii) The main color shown on the TV screen is steady green during the game but the color during commercial breaks and the halftime show would change frequently [7], which results in the ever-changing electricity consumption of TV screens and frequency fluctuations. iv) The duration of the halftime show is much longer than regular commercial breaks, so it can be inferred that more viewers would tend to have a rest and use additional electrical household appliances compared with regular commercial breaks, resulting in a sharper frequency drop. On the contrary, frequency rises can be observed after commercial breaks and the halftime show but their slopes are gentler than those of frequency drops. The reason is that viewers tend to begin to use electrical household appliances simultaneously once commercial breaks or the halftime show begin, but the using time varies for different people. Therefore, the frequency rises are not quite as sharp. In other words, simultaneous beginnings of using lead to sharp frequency drops while more random endings of using lead to gentler frequency rises.

To better illustrate the events detected during Super Bowl LIV, the detailed views of one load shedding event during the halftime show and one generation trip event during commercial breaks in the EI power system are given in Figs. 6 and 7, respectively. It is noted that different colors denote the data measured by different FDRs and there are 50 FDRs in total for this case.

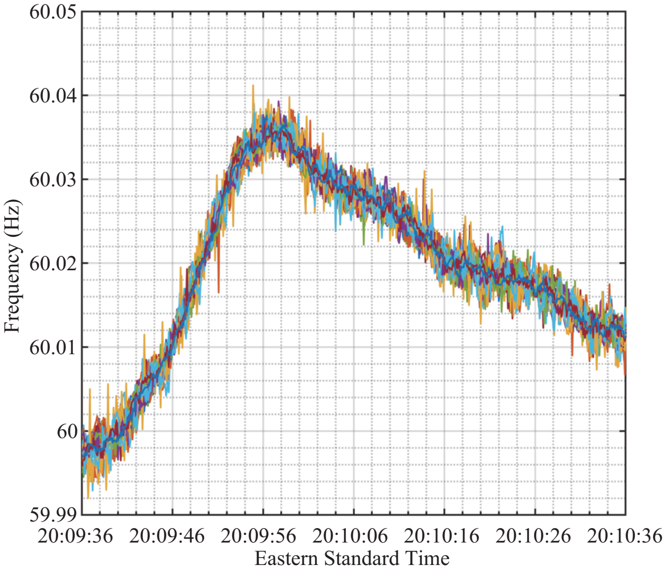


Fig. 6. Load shedding event detected at 20:09:51 in the EI power system during the halftime show of Super Bowl LIV.

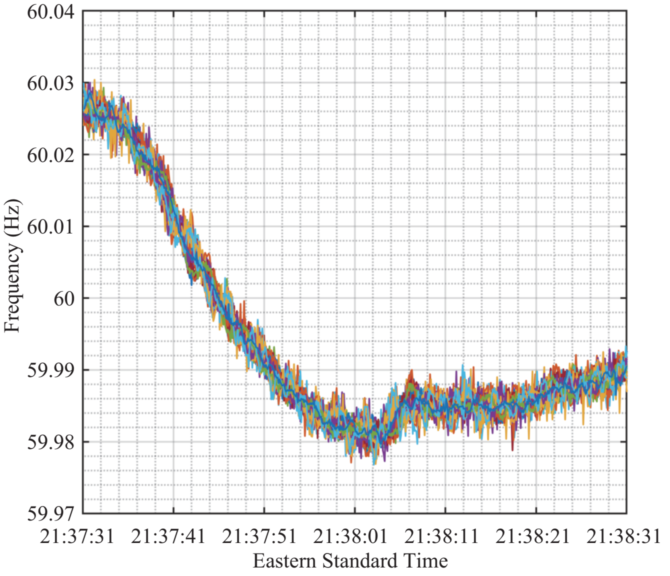


Fig. 7. Generation trip event detected at 21:37:46 in the EI power system during the halftime show of Super Bowl LIV.

It can be seen from Fig. 6 that the system frequency rises from 59.995 Hz to 60.035 Hz, which indicates that hundreds of megawatt power surplus occurred within half a minute, assuming the frequency governing characteristic (i.e., β) for EI power systems is 15 GW–25 GW/Hz [7]. Similarly, it can be seen from Fig. 7 that the system frequency drops from 60.028 Hz to 59.980 Hz, which indicates hundreds of megawatt active power deficiencies. In summary, the simultaneous electricity consumption activities of people during Super Bowl Sunday would cause more frequency events in power systems. To demonstrate this point, the frequency fluctuations in EI, WECC and ERCOT power systems during Super Bowl LIV Sunday (i.e., 2020/02/02) and an ordinary Sunday are respectively shown in Figs. 8(a), (b) and (c).

It can be seen from Fig. 8 that the magnitudes of frequency fluctuations during Super Bowl Sunday are obviously higher than the ones during the previous Sunday in all three power systems, which indicates that simultaneous festival activities would greatly impact the power balance and result in more difficulties in frequency regulation. To show the differences of frequency fluctuations between Super Bowl Sunday and an ordinary Sunday more clearly, their histograms are given in Fig. 9. It can be seen from Fig. 9 that the ranges of frequency fluctuations in the three power systems during Super Bowl Sunday are all much larger than the ones during an ordinary Sunday and the possibility of frequency during an ordinary Sunday is denser at around 60 Hz. In other words, the variance and skewness of frequency during Super Bowl Sunday are higher than those during an ordinary Sunday, which means that the frequency quality of an ordinary Sunday is better while simultaneous human activities would cause deterioration.

IV. COMPARISONS FOR THE FREQUENCY FLUCTUATIONS BETWEEN SUPER BOWL LIV AND THE PREVIOUS SUPER BOWL GAMES

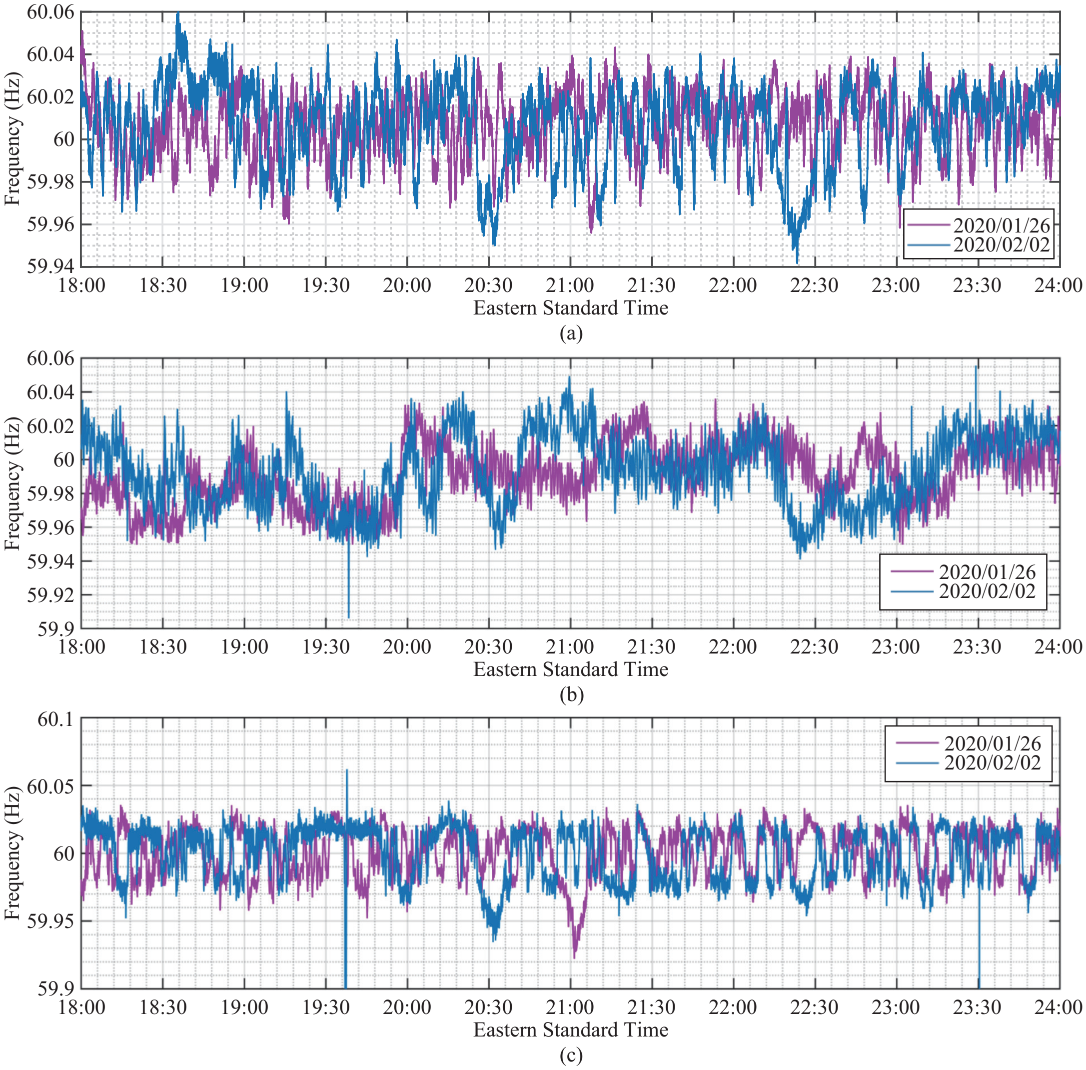
With the rapid developments of technology, the structure of power systems and the life-style of humans also changed significantly. Therefore, the frequency fluctuations during Super Bowl Sunday of the past several years and the number of viewers and events during Super Bowl Sunday in the past several years are also analyzed in this study, as shown in Fig. 10.

It can be seen that the number of viewers is always around 100 million while there is a decreasing trend for the events detected in the past decade. The reasons could be that more and more viewers use the Internet rather than TV to watch the game, so there are different delays for different viewers, which reduces the simultaneity of electricity consumption among viewers. Therefore, the sudden power imbalance occurs less frequently in recent years and fewer events are detected.

To show this point more clearly, the frequency fluctuations during Super Bowl Sunday of 2018, 2019 and 2020, and their statistics are respectively shown in Fig. 11 and Table II. In addition, the detailed views for their beginnings of halftime

TABLE II
STATISTICS OF FREQUENCY FLUCTUATIONS DURING SUPER BOWL SUNDAY IN 2018, 2019 AND 2020

Year	Mean	Variance	Skewness	Kurtosis
2018	60.00417	3.27632×10^{-4}	−0.44119	−0.20680
2019	60.00301	2.98383×10^{-4}	−0.23361	−0.57038
2020	60.00679	3.75349×10^{-4}	−0.58390	−0.22318



(a)

(b)

(c)

Fig. 8. Frequency fluctuations in different power systems during Super Bowl LIV Sunday and its Previous Sunday. (a) EI power system. (b) WECC power system. (c) ERCOT power system.

shows are also given in Fig. 12. The definitions of the four statistics of frequency data (i.e. mean, variance, skewness and kurtosis) are respectively given as follows.

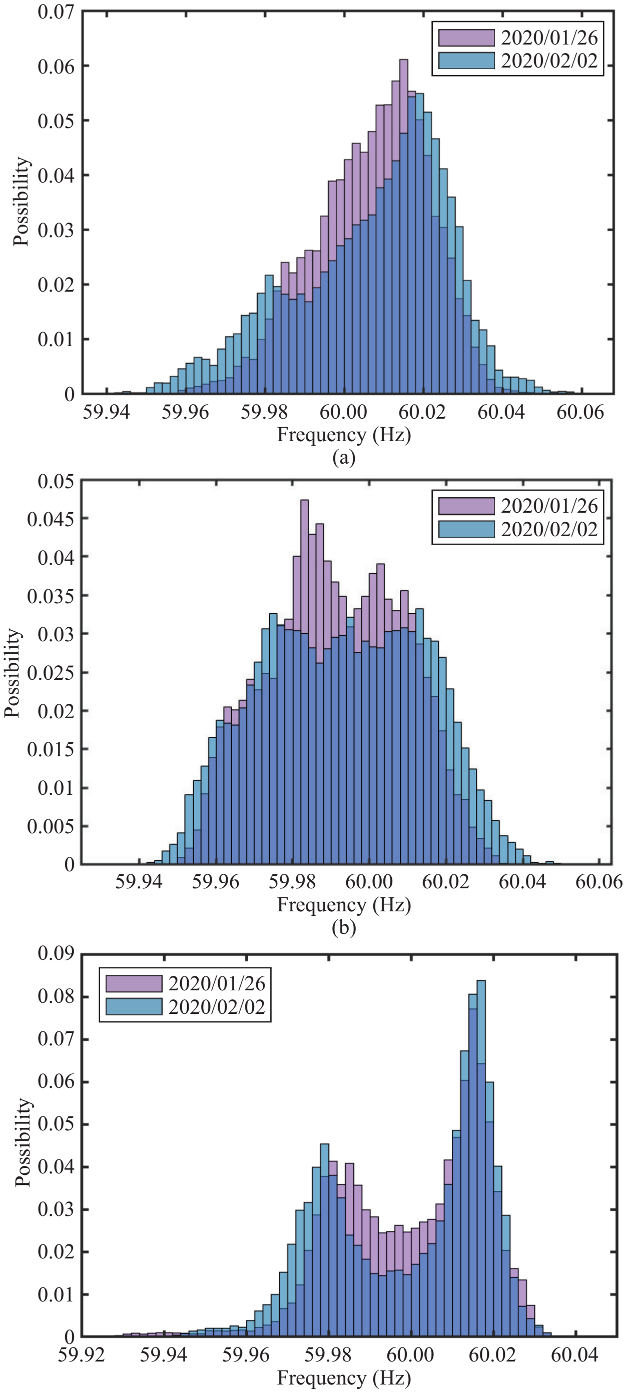
$$f_{\text{mean}} = \frac{1}{T}\sum_{t=1}^{T} f_t \tag{2}$$

$$f_{\text{variance}} = \frac{1}{T}\sum_{t=1}^{T} (f_t - f_{\text{mean}})^2 \tag{3}$$

$$f_{\text{skewness}} = \frac{\frac{1}{T}\sum_{t=1}^{T} (f_t - f_{\text{mean}})^3}{\left[\frac{1}{T}\sum_{t=1}^{T} (f_t - f_{\text{mean}})^2\right]^{\frac{3}{2}}} \tag{4}$$

$$f_{\text{kurtosis}} = \frac{\frac{1}{T}\sum_{t=1}^{T} (f_t - f_{\text{mean}})^4}{\left[\frac{1}{T}\sum_{t=1}^{T} (f_t - f_{\text{mean}})^2\right]^{2}} - 3 \tag{5}$$

where T is the total time points, respectively. It is worth mentioning that: i) f_{mean} measures the long-term average operation frequency in power systems. ii) f_{variance} measures magnitudes of long-term frequency variations in power systems. iii) f_{skewness} measures the asymmetry of frequency data distribution [20] and is equal to 0 if it is symmetric. f_{skewness} would be negative if the frequency data is spread out more to the left of the mean than to the right, and would be positive if the frequency data is spread out more to the right. iv) f_{kurtosis} measures the outlier-prone of the frequency data distribution when compared with the Gaussian distribution [21]. f_{kurtosis} would be greater than 0 if the frequency data distribution is more outlier-prone than the Gaussian distribution, and smaller than 0 otherwise. It can be seen from Fig. 11 and Table II that the variance and skewness in 2020, 2018 and 2019 are with the largest, medium and smallest absolute values, which indicates that the magnitude of long-term frequency variation in 2020 is highest and its distribution shape largely shifts to the left. One possible reason is that the average size of the TV screen increases from 45.2 inches (2018) to 47.9 inches (2020) [22]



(a)

(b)

(c)

Fig. 9. Histograms of system frequencies for different power systems during Super Bowl Sunday and its Previous Sunday. (a) EI power system. (b) WECC power system. (c) ERCOT power system.

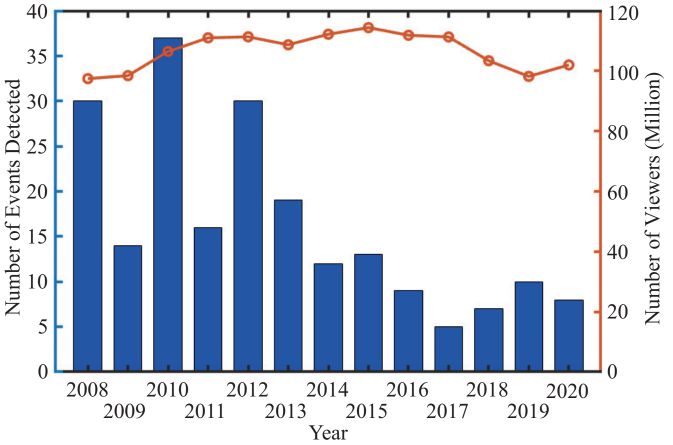


Fig. 10. Number of viewers and events during Super Bowl Sunday in the past several years.

which enlarges the differences of electricity consumption when displaying the bright and dark images during the game and continuously causes relatively larger frequency variations. However, the magnitude of long-term frequency variations in 2019 is smallest and its distribution shape slightly shifts to the left. In addition, the kurtosis in 2019 is the smallest, which indicates that the frequency distribution in 2019 is more similar to the Gaussian distribution when compared with 2018 and 2020. The reason could be that the number of viewers in 2019 is the fewest as shown in Fig. 10, which leads to a smaller impact of simultaneous activities when compared with 2018 and 2020. It should be clarified that the number of viewers can only impact the frequency fluctuation to a certain extent and the variance and skewness can only reflect the frequency fluctuation in one aspect. Therefore, the number of events detected may not have a strict relationship with them. However, after reviewing the event reports for the 11 events detected during Super Bowl Sunday in 2019, it was found that in fact one and two of them respectively happened in pumped storage plants in Northfield and Florida, MA, which are scheduled economic dispatches by the Northeast Power Coordinating Council (NPCC). Therefore, there are only 8 unexpected events that truly happened during Super Bowl Sunday in 2019.

Although the frequency variance in 2020 is the largest one that indicates the largest frequency variation in the long-term view, its sudden frequency change in the short-term view caused by simultaneous activities is smaller than the ones in past years. The most representative simultaneous activities would occur at the beginning of the halftime show, because it is the longest break during the Super Bowl game and most viewers would switch to other activities at this time. It can be seen from Fig. 12 that the sudden frequency drop in 2020 is much less than the ones in 2019 and 2018, and there is a decreasing trend in the intensity of sudden frequency drops at the beginning of halftime with the year, which demonstrates that variable delays caused by the increasing utilization of Internet video streaming would lighten the simultaneity of the electricity consumption of Super Bowl viewers. According to Refs [23]–[25], the average minute audience in the stream-living platform (i.e., Internet viewers per minute) in 2018, 2019 and 2020 are 2.02 million, 2.60 million and 3.40 million, respectively. It can be seen that the Internet viewers do quickly increase each year and can have potential impacts on electricity consumption.

It should be mentioned that the annual frequency fluctuation phenomenon is different, which may be caused by many reasons, e.g., the structure of the power system is changing,

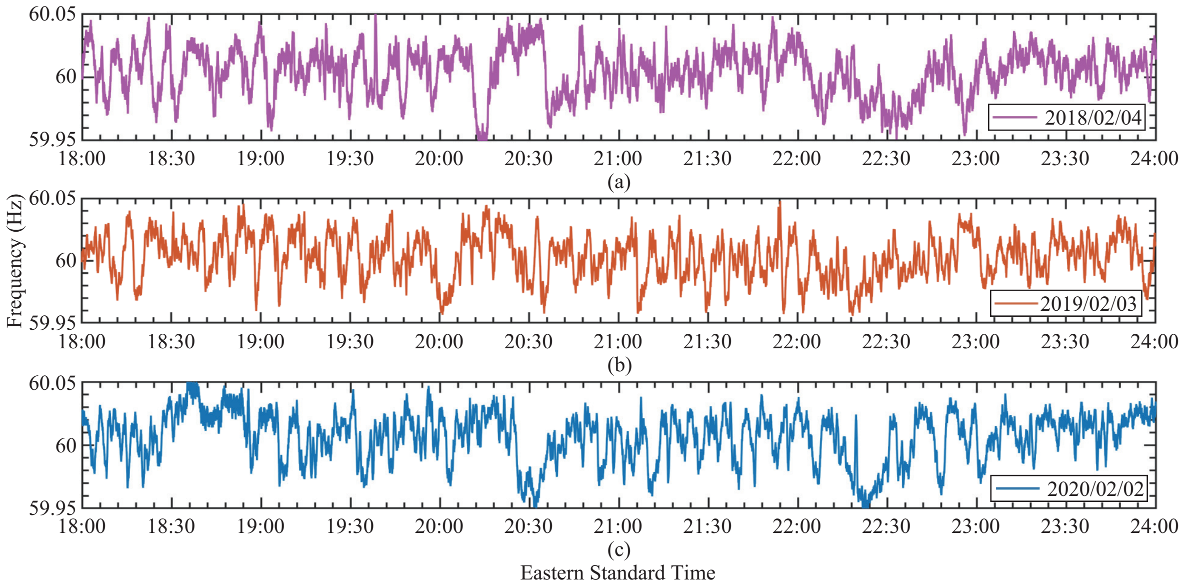


Fig. 11. Frequency fluctuations in the EI power system during Super Bowl Sunday in (a) 2018, (b) 2019 and (c) 2020.

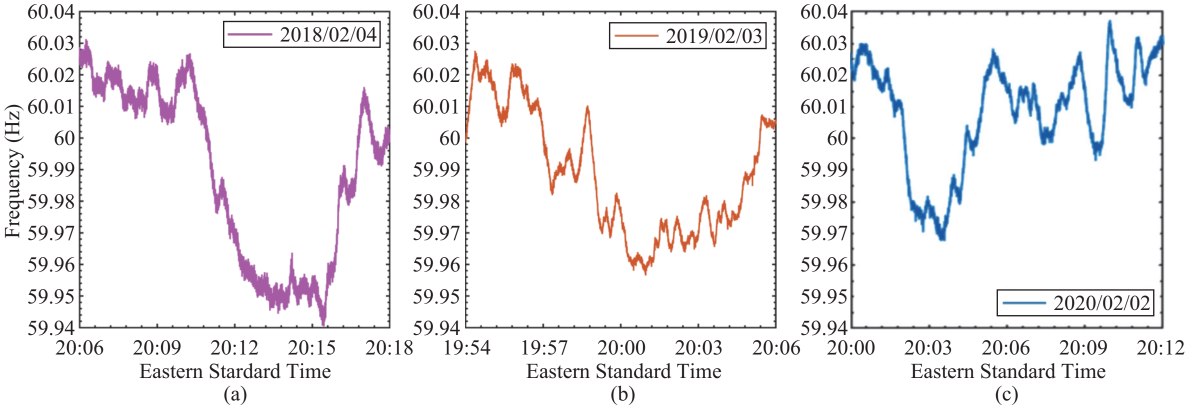


Fig. 12. Detailed frequency drops of viewers in the EI power system at the beginning of the halftime show in (a) 2018, (b) 2019 and (c) 2020.

the penetration of renewable energy sources is increasing, the size of TV screens is increasing, and the viewers using the Internet for viewing are increasing. Although this study presents several possible reasons for the annual frequency fluctuations during Super Bowl Sunday, these reasons should be further studied and investigated with more data and surveys in the future.

V. DISCUSSIONS ABOUT THE THEORETICAL CAUSES OF FREQUENCY FLUCTUATIONS AND CORRESPONDING CONTROL MEASURES

Although several reasons for frequency fluctuations are given in the previous sections, they are on a case by case analyses. Therefore, this section briefly introduces the theoretical causes of frequency fluctuations and corresponding control measures.

Generally speaking, the nature of frequency fluctuations is the results of competition between power imbalance and frequency control measures. The unexpected and unavoidable power imbalance will cause frequency deviations, and the frequency control measures limit the extent of the deviations and regulate the frequency to return to the nominal value as soon as possible. Since there are inevitable delays in the control measures, the frequency of power systems always fluctuates. However, the frequency fluctuations are not too severe for most situations. During the Super Bowl Sunday, it is the simultaneous activities that cause a severer sudden power imbalance, which causes larger and visible frequency fluctuations and even load shedding or generation trip events.

Generally, all generator groups in power systems have an automatic speed regulation system. They jointly undertake the task of primary frequency regulation (i.e., primary frequency control), whose main goal is to respond to the random changes of the active load of the whole system. Of course, it also plays a role in the slow changes of the load.

In order to explain the principle and performance of the primary frequency regulation, the frequency characteristics of the equivalent generator groups and total load (including network loss support and power plant consumption) of the given power system should be considered together. In Fig. 13, lines 1 and 2 represent the frequency characteristics of the equivalent generator groups and total load, respectively. Their intersection o corresponds to the equilibrium point between the output power of the equivalent generator groups (i.e., P_{G0}) and the active power absorbed by the total load (i.e., P_{L0}). In addition, the system frequency is exactly equal to an ideal steady-state operation condition of the rated frequency f_N. The change of the steady-state operating point is analyzed when the total load increases ΔP_{L0}. After the load increases, the frequency characteristic of the load will move upward and become line 3 in Fig. 13. In this case, if the rated frequency of the system remains unchanged, the active power absorbed by the load will increase from P_{L0} to $P_{\mathrm{L0}} + \Delta P_{\mathrm{L0}}$, which is equivalent to point A on line 3. However, in practice, the new steady-state operating point is o' at the intersection of lines 1 and 3, where the output power of the equivalent generator groups reaches a new balance with the active power taken by the increased load, while the frequency of the system decreases to a certain extent [26].

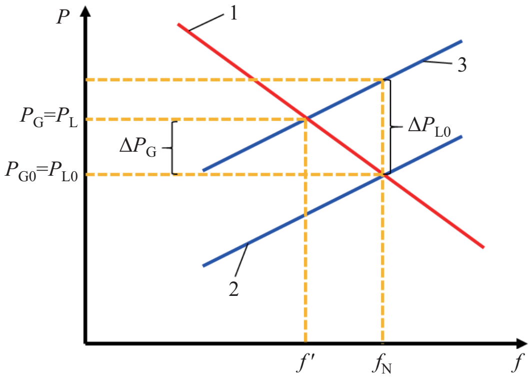


Fig. 13. Static power-frequency characteristics of power systems.

The control measures for frequency regulation in different scenarios can be divided into four types, i.e., primary control, secondary control, tertiary control, and time control. The timescales of these control measures are different and are shown in Fig. 14. For the frequency fluctuations during Super Bowl Sunday, most control measures are primary control and secondary control while few scenarios may need tertiary control. These three control measures are well-known and more details can be found in [26]. Time control is a little special and it aims to maintain the long-term average frequency to the rated frequency (i.e., 60 Hz in U.S. power systems) by "time error correction" in the scheduled dispatch [27]. All four types of control measures consist of the basic measures for frequency regulation. They work cooperatively to maintain the nominal frequency and avoid extreme frequency deviations.

VI. CONCLUSION

This paper investigates the frequency fluctuations in EI, WECC and ERCOT power systems caused by simultaneous human activities during Super Bowl games, and several possible explanations for these phenomena are explored. The conclusions of this study can be summarized as follows.

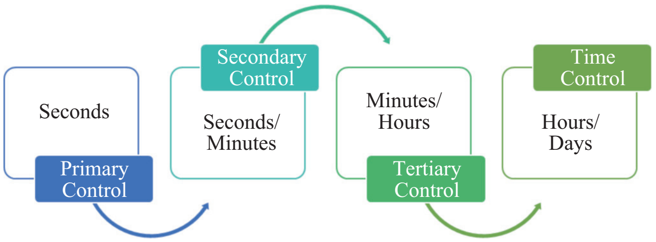


Fig. 14. Four different types of frequency control measures.

1) Simultaneous human activities definitely influence the frequency in power systems, and comparisons show that the magnitude of frequency fluctuations during Super Bowl Sunday is much higher than during an ordinary Sunday. The reason could be that a part of the viewers would simultaneously use electrical household appliances once commercial breaks occur or the halftime show begins, which results in sudden power imbalances and frequency fluctuations.

2) Comparisons among different years show that the long-term variance of frequency in 2020 is the largest one. The reason could be that the size of the TV screen is increasing, which leads to a larger power imbalance when the images switch from bright to dark or in reverse. Exceptionally, the smallest variance in 2019 is a result of its fewest viewers, which weakens the influence of simultaneous activities.

3) The sharpest frequency drops appear at the beginning of the halftime show while the frequency rises at the end of the halftime show are flatter. The reasons could be that more viewers would begin to simultaneously use electrical household appliances at the beginning of this longest break while stopping their usage and coming back to watch the game at different times.

4) There is a decreasing trend for the magnitude of sudden frequency changes in Super Bowl games during the past few years. The reason is that more and more viewers use Internet-based portable devices to watch the game, such as tablet computers and smartphones. Different time delays of these devices will lighten the simultaneity of electricity consumption of Super Bowl viewers at the beginning of commercial breaks or the halftime show. Although the increase of the screen size of TVs will exacerbate the absolute value of power imbalance, the impact of the increase in Internet viewers for lightening the simultaneity of electricity consumption is even greater.

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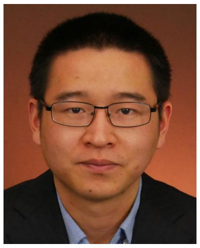

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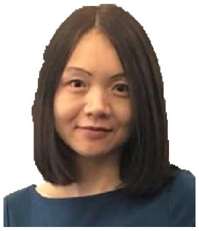

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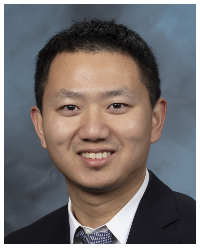

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