3D-PEIM
INTERNATIONAL SYMPOSIUM
ON 3D POWER ELECTRONICS
INTEGRATION AND MANUFACTURING

FIU
Energy Power & Sustainability
FLORIDA INTERNATIONAL UNIVERSITY

Reliability Analysis of Wireless Power Transfer for Electric Vehicle Charging Based on Continuous Markov Process

Milad Behnamfar, Md Abu Taher, Alexis Polowsky, Sukanta Roy, Mohd Tariq, Arif Sarwat

Department of Electrical and Computer Engineering, Florida International University

Presented by:

Milad Behnamfar

Graduate student, Energy, Power, Sustainability, Intelligence Lab

Florida International University

Date: 1 February 2023

Highlights:

1. Motivation & Introduction
2. Circuit and Block diagram
3. Methodology: Continuous Markov Process
4. Reliability Analysis of System and Their Results
5. Conclusion & Future works

Motivation:

- ✓ People may forget to plug-in and find themselves out of battery energy later on
- ✓ The charging cables on the floor may bring tripping hazards
- ✓ Leakage from cracked old cable, in particular in cold zones, can bring additional hazardous conditions to the owner
- ✓ People may have to brave the wind, rain, ice, or snow to plugin with the risk of an electric shock.
- ✓ Wireless power transfer for electric vehicle charging address the drawbacks of plug-in charging.
- ✓ For a stationary WPT system, the drivers just need to park their car and leave.
- ✓ For a dynamic WPT system, which means the EV could be powered while driving

Benefits of Wireless Charging

✓ For stationary charging in the harsh weather environment, the driver does not need to drop off for charging.

✓ In the dynamic charging, the EV is possible to run forever without a stop.

✓ The battery capacity of EVs with wireless charging could be reduced to 20% or less compared to EVs with conductive charging.

✓ As the battery size can be reduced, the cost of electric vehicle can be decreased as a result.

Fig. 1. A Taxi driver is happily staying in his car while charging up wirelessly.

Introduction:

✓ Wireless power transfer is a practical technology for charging electric vehicles.

✓ As wireless charging for EV is growing where much research ranging from improving efficiency to improving misalignment has been done in this area.

✓ The reliability analysis for wireless charging of electric vehicles is missing in the literature.

✓ Reliability analysis of wireless charger is required as it is installed in varying environments in which harsh conditions could have adversely affected the performance of components.

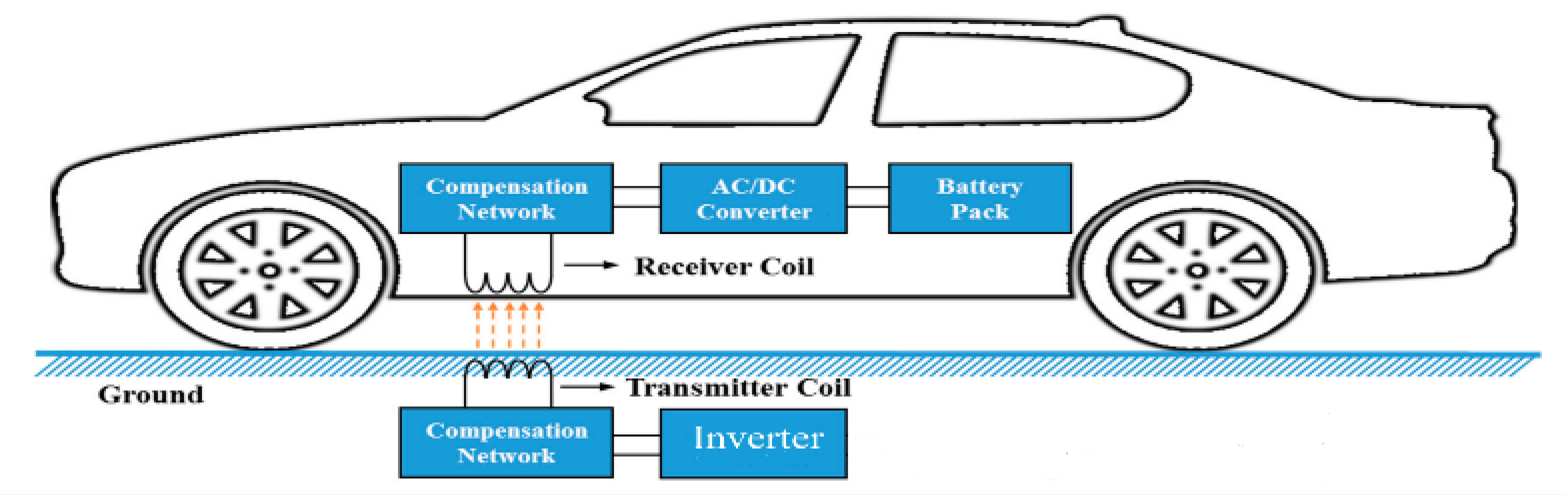

Fig. 2. Typical inductive power transfer for charging electric vehicles

Circuit and Block Diagram:

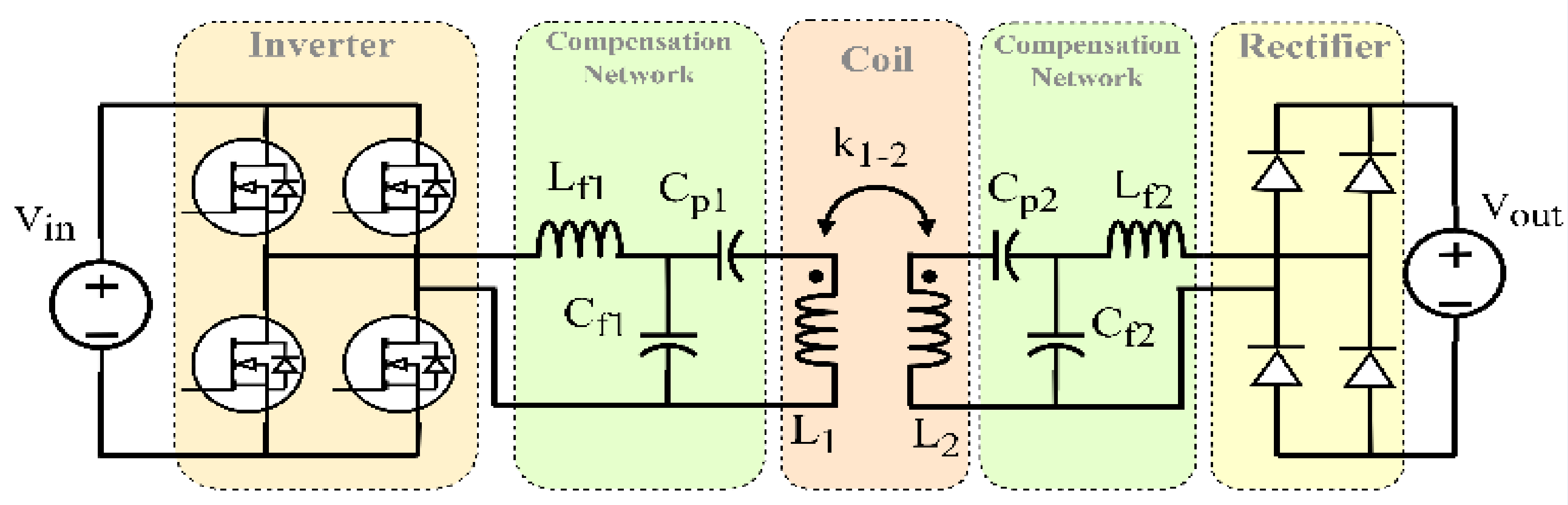

Fig. 3. Circuit topology of IPT system with LCC compensation network for charging EVs

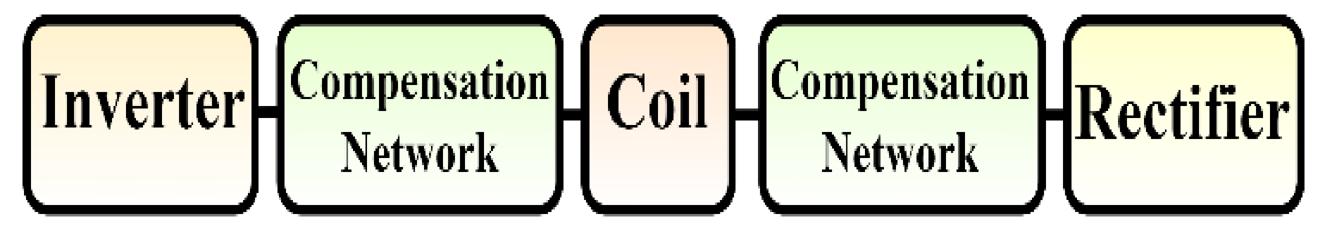

Fig. 4. Block diagram of the entire system

Methodology: Continuous Markov Process

- ✓ Continuous Markov is a powerful method that is founded on multiple system states and transition phenomena
- ✓ Markov process is a well-developed technique to model complex reliability problems to simulate models in an analytical way
- ✓ Markov process stands on two fundamental principles: 1) state transition is constant and 2) any state transition does not depend on the previous state
- ✓ Several states can be defined based on the system transition direction and components involved to be modeled in the analysis process
- ✓ The continuous Markov process uses a constant state transition rate throughout the analysis period
- ✓ State transition in this process is defined by a constant failure rate

$$Reliability = e^{-\lambda_p t} \tag{1}$$

Reliability Analysis of Inverter

✓ The inverter is the fundamental part of wireless a charging system. Hence, its reliability assessment is the utmost requirement to evaluate the reliability of the whole wireless charging system

✓ Inverters are mainly composed of four elements that are primarily identified as IGBT, DC-link capacitor, Microcontroller, and Colling fan

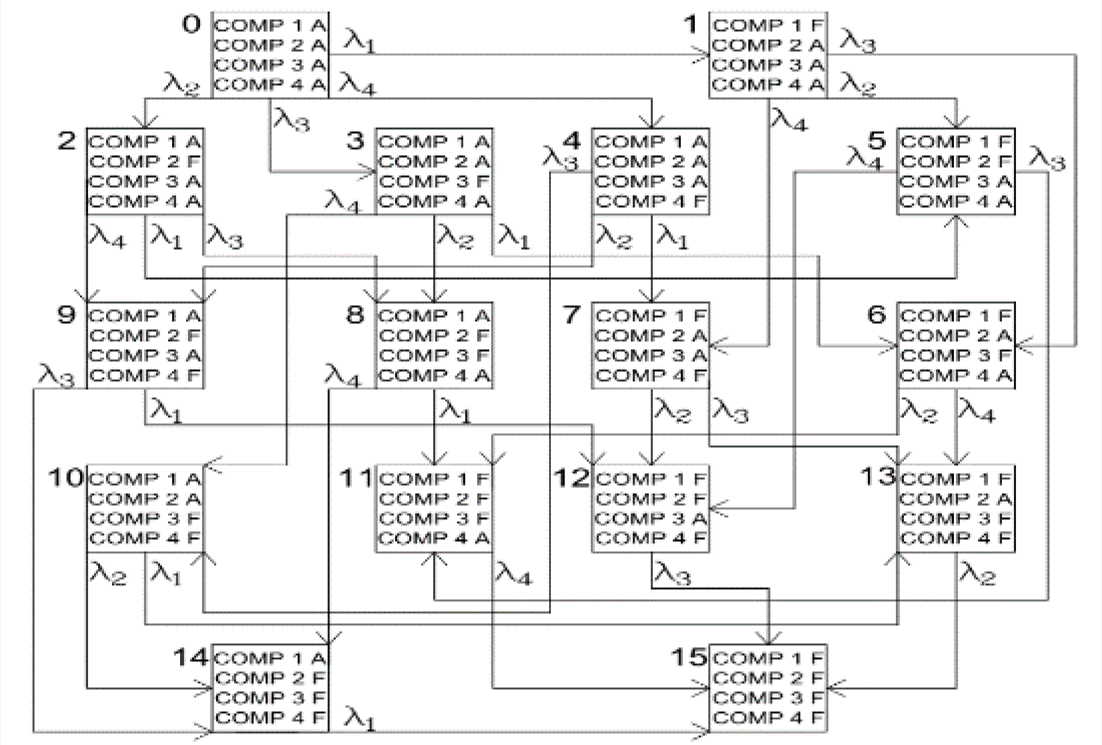

Fig. 5. state diagram of an inverter composed of four non-similar components

Result of Inverter Reliability

Table 1. Failure Rates of Inverter Components

Components	Failure rate (per year)
IGBT	$\lambda_p = \lambda_b \pi_T = 0.3436 \times 10^{-4}$
DC-link capacitor	$\lambda_p = \lambda_b \pi_v \pi_Q \pi_T = 0.447 \times 10^{-4}$
Microcontroller	$\lambda_p = \lambda_b \pi_v \pi_T = 0.603 \times 10^{-4}$
Cooling fan	$\lambda_p = 0.01041$

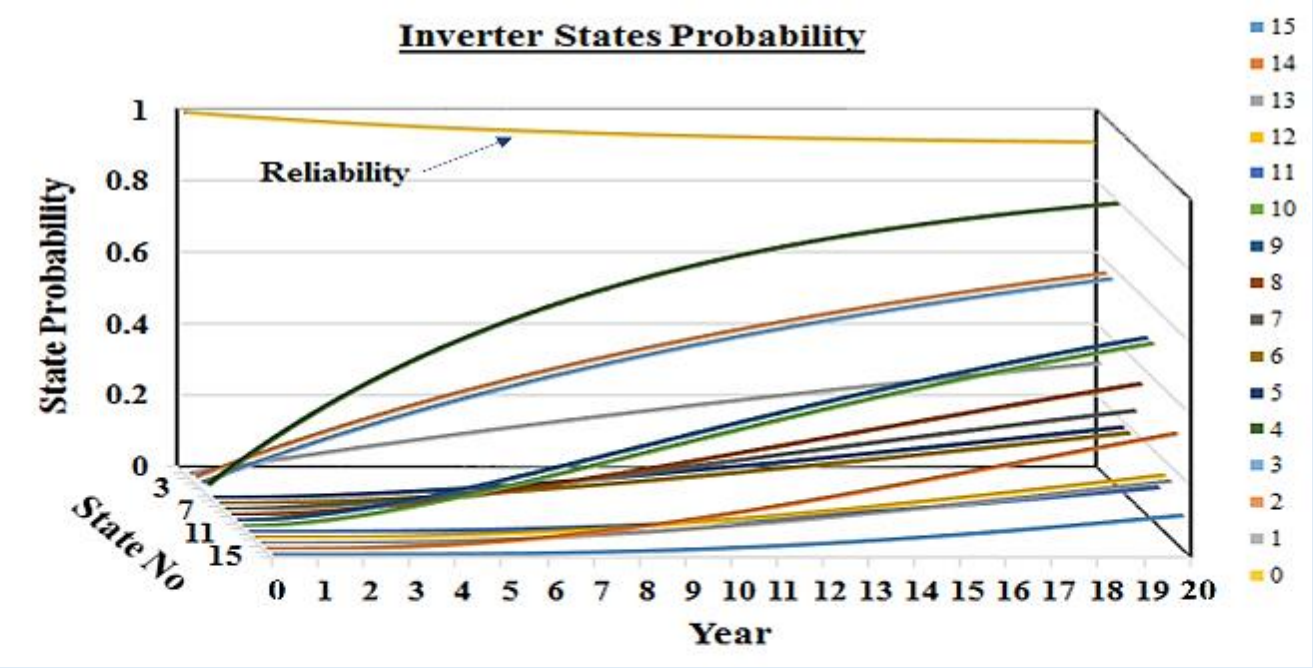

Fig. 6. Inverter reliability and states probability in a 20-year lifetime

Reliability Analysis of Compensation Network:

- ✓ The main reason to use compensation network is to reduce the reactive power, which lead to improving efficiency.
- ✓ LCC-Compensation network proved to be the most efficient topology as performs a current source for both primary and secondary
- ✓ LCC-Compensation efficiency is high at different load conditions.

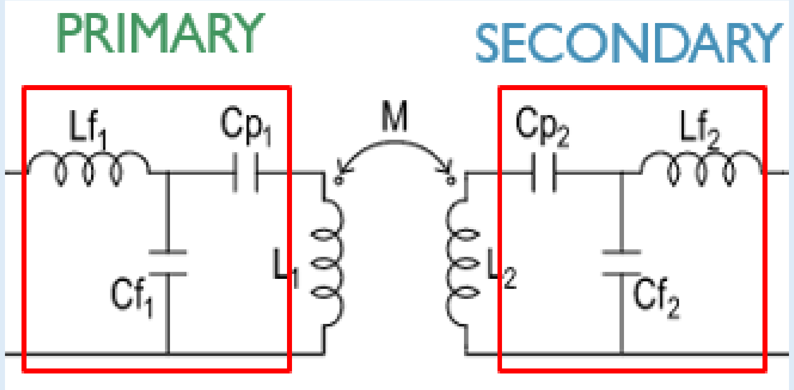

Fig. 7. LCC-Compensation Network Primary & Secondary Circuit

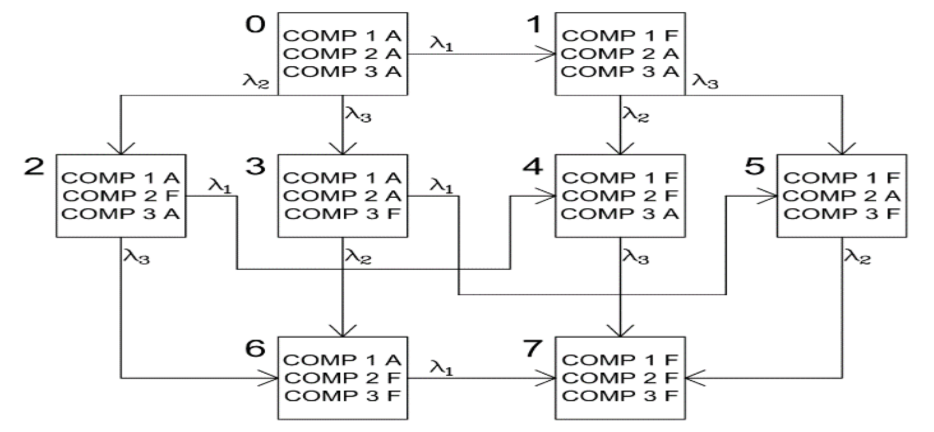

Fig. 8. Compensation Network State Diagram

Result of Compensation Network Reliability:

The failure rate of the capacitor is calculated as follows:

$$\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \frac{Failures}{10^6 hours} \qquad (2)$$

λ_b = Base failure, , π_T= Temperature Factor, π_C= Capacitor Factor, π_v = Voltage Sterss Factor,
π_{SR} = Series Resistance Factor, π_Q = Quality Factor, π_E = Environment Factor

The failure rate of the inductor is calculated as follows:

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E \frac{Failures}{10^6 hours} \qquad (3)$$

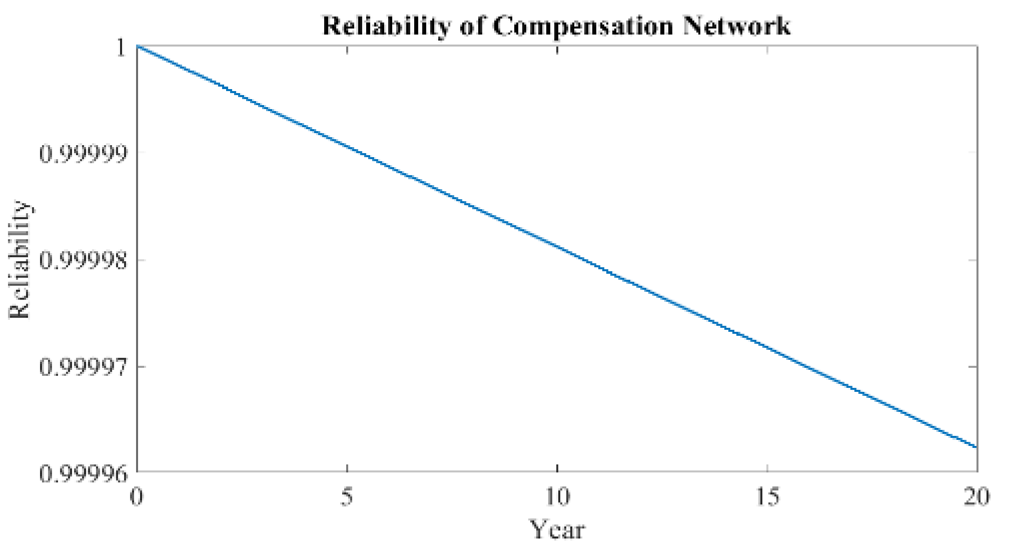

Fig. 9. Reliability of the compensation network in a 20-year lifetime

Reliability Analysis of Coil:

- ✓ The inductive coil is used and the frequency of the system is in the range of 35-85 kHz.
- ✓ The performance of the Inductive coil is similar to the RF transformer.
- ✓ As the failure rate for the litz wire in high frequency is not available, the failure rate of RF transformer is used.
- ✓ The failure rate of the coil is calculated by eq. 1:

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E \frac{Failures}{10^6 hours} \qquad (4)$$

Where

λ_b is base failure rate , π_T is Temperature factor , π_Q is quality factor , π_E is environment factor

Result of Coil Reliability:

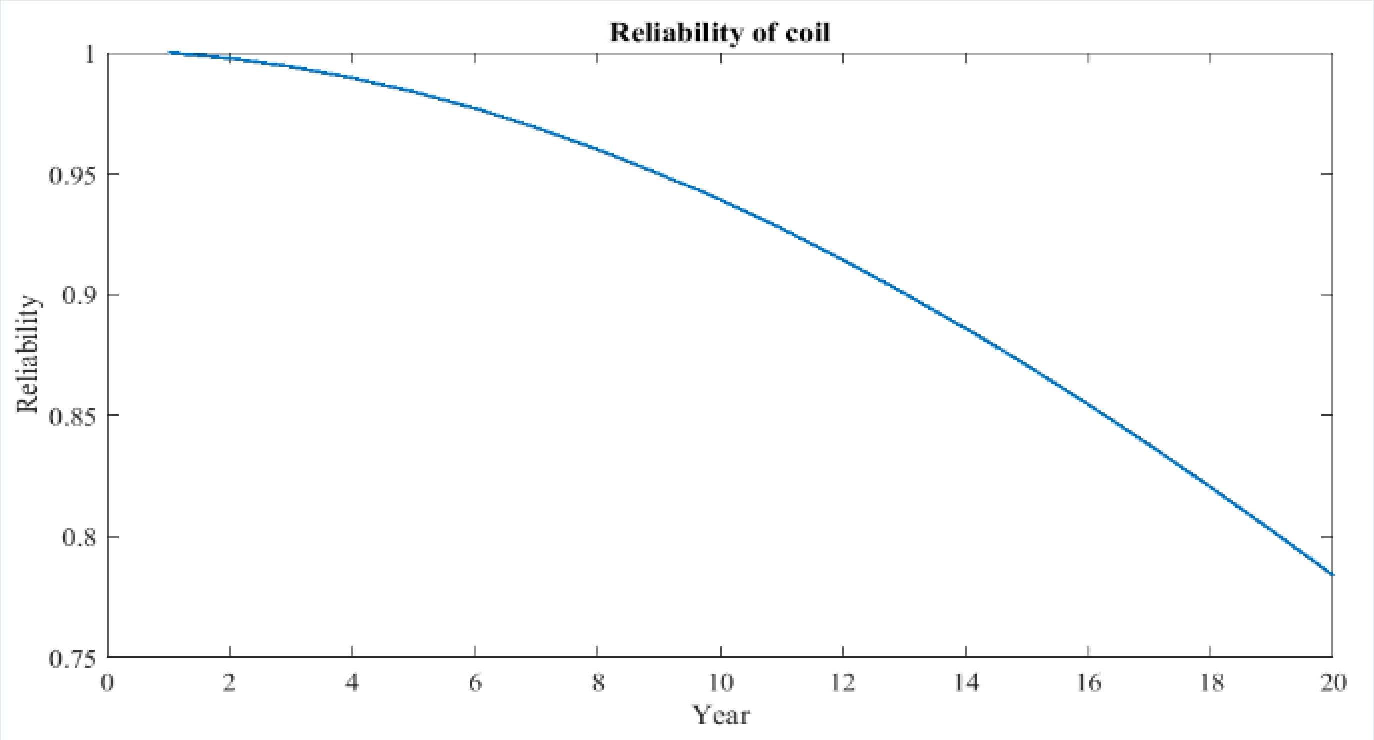

Fig. 10. Reliability of coil in a 20-year lifetime

Reliability Analysis of Rectifier:

- ✓ The rectifier is composed of four similar diodes.
- ✓ As diodes are similar, the reliability analyses for rectifier behave as one component with two states.
- ✓ The failure rate of the rectifier is calculated by eq. 1:

$$\lambda_p = \lambda_b \pi_T \pi_S \pi_C \pi_Q \pi_E \frac{Failures}{10^6 hours} \tag{5}$$

Where

λ_b is base failure rate , π_T is Temperature factor , π_S is electrical stress factor , $\pi_Q$is quality factor ,

π_C is contact construction factor , π_E is environment factor

Result of Rectifier Reliability:

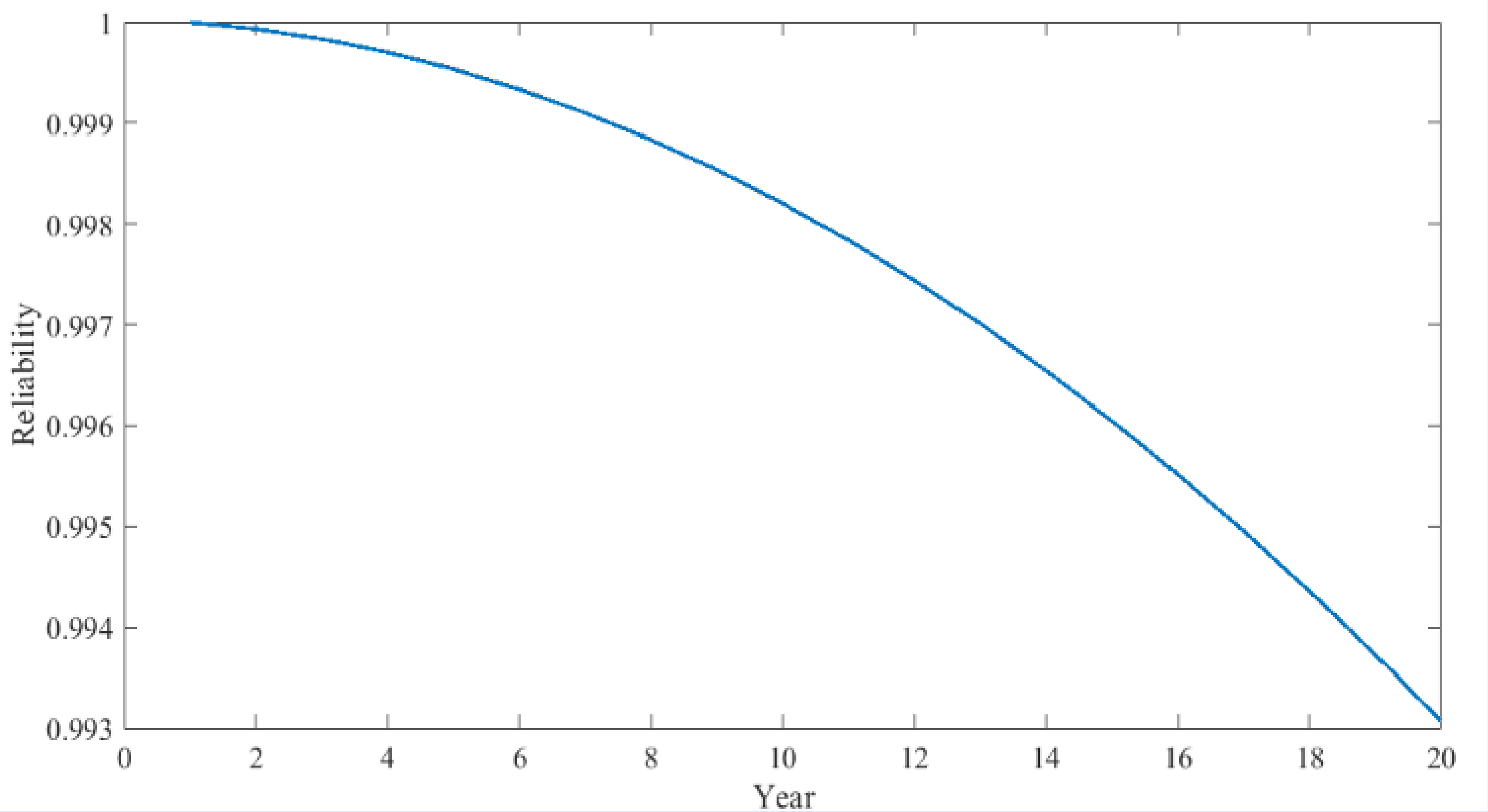

Fig. 11. Reliability of Rectifier in a 20-year lifetime

Result of the Overall System Reliability:

TABLE 2. FAILURE RATES OF COMPONENTS IN COMPENSATION NETWORK, COIL, RECTIFIER

Component	Failure rate per year
Inductor (L_{f1},L_{f2})	1.19×10^{-4}
Capacitor (C_{f1},C_{f2})	0.406×10^{-4}
Capacitor (C_{P1},C_{p2})	0.289×10^{-4}
Coil	11.65×10^{-4}
Diode	33.288×10^{-6}

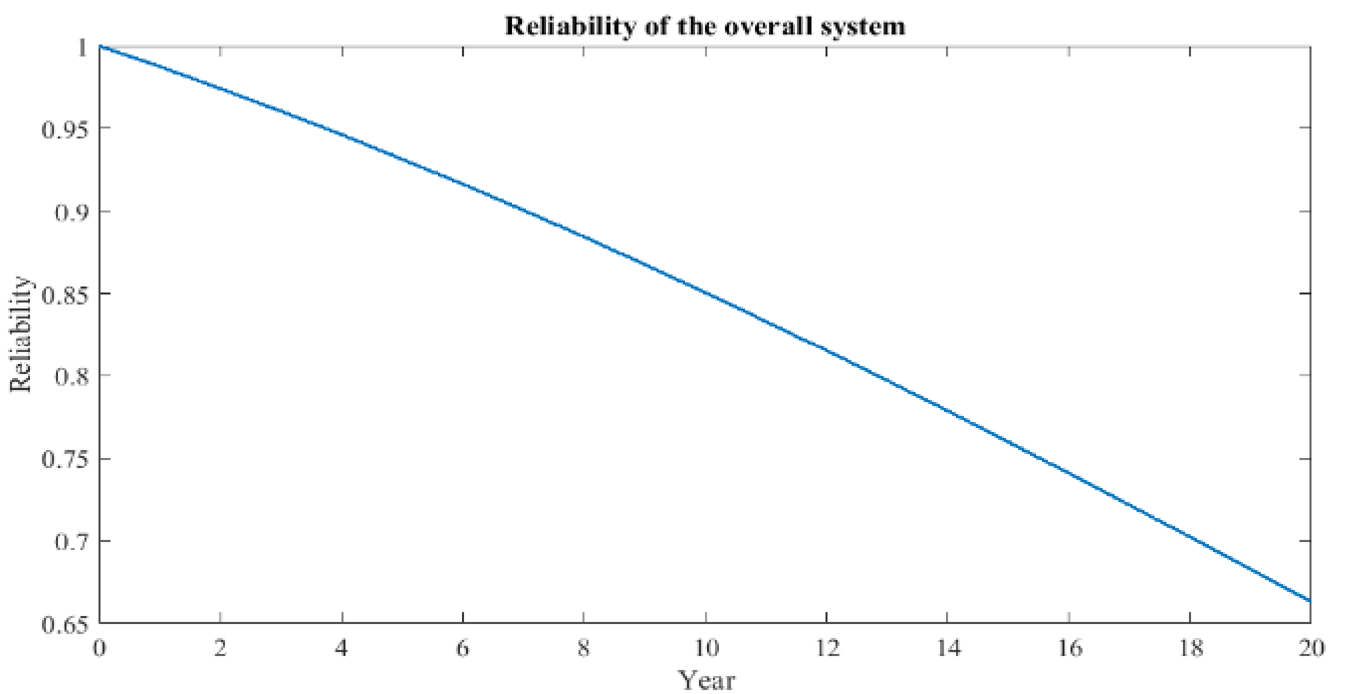

Fig. 12. Reliability of the overall system in a 20-year lifetime

Conclusion:

- ✓ Continuous Markov process is utilized to determine the overall reliability of wireless power transfer setup for EV charging
- ✓ The system consists of five main sections, which are connected in series
- ✓ The reliability of each section has been calculated and multiplied to conclude the reliability of the overall system
- ✓ The results show an overall dependable lifetime of as long as twenty years with 66.31% availability
- ✓ Inverter and the coil are the most contributors of decreasing the reliability of the overall system, which their availability after twenty year life time are 87.36% and 76.49% respectively.

Future work

- ✓ Reliability analysis of different circuit topologies of wireless chargers.
- ✓Applying Monte Carlo simulation for analyzing reliability the system when controllers, communication are used.
- ✓ Investigating of wireless charger’s structures to provide parallel path to improve reliability.
- ✓ Reliability analysis of the system by considering foreign objects near the coil.
- ✓ Reliability analysis consider the weather and comparing the reliability of the system in different conditions.

References:

[1] H. Jafari, M. Moghaddami, T. O. Olowu, A. Sarwat, M. Mahmoudi “Virtual Inertia-Based Multi-Power Level Controller for Inductive Electric Vehicle Charging Systems,” IEEE Journal of Emerging and Selected Topics in Power Electronics, pp 1-1, 2020.

[2] M. Behnamfar, H. Javadi, E. Afjei, “A dynamic CPT system LCCompensated with a six-plate capacitive coupler for wireless charging of electric vehicle in motion,” 2020 28th Iranian Conference on Electrical Engineering (ICEE), 2020.

[3] M. Lu and K. D. T. Ngo, “Systematic design of coils in series–series inductive power transfer for power transferability and efficiency,” IEEE Trans. Power Electron., vol. 33, no. 4, pp. 3333–3345, Apr. 2018.

[4] M. Behnamfar, H. Jafari, A. Sarwat, “Development of a Mixed Inductive and Capacitive Wireless Power Transfer to Improve Misalignment Performance for Charging Electric Vehicles,” 2022 IEEE Transportation Electrification Conference & Expo (ITEC), 2022.

[5] A. Soldati; G. Pietrini;M. Dalboni; C. Concari, “Electric-vehicle power converters model-based design-for-reliability,” CPSS Transactions on Power Electronics and Applications, Vol.3, pp. 102-110, 2018.

[6] D. K. Murugesan, I. Manickam, “Reliability and cost analysis of different Power inverter topologies in Electric Vehicles” IEEE Transportation Electrification Conference and Expo (ITEC), 2015

[7] B. K. Talukdar and B. C. Deka, “An approach to reliability, availability and maintainability analysis of a plug-in electric vehicle,” World Electric Vehicle Journal, vol. 12, no. 1, p. 34, 2021

References:

[8] X. Shu, W. Yang, Y. Guo, K. Wei, B. Qin, G. Zhu, “A reliability study of electric vehicle battery from the perspective of power supply system,” J. Power Sources 451 (2020), 227805.

[9] M. Ghavami and C. Singh, “Reliability Evaluation of Plug-in Hybrid Electric Vehicle Chargers,” Proc. of IEEE 2017 EEEIC / I&CPS Europe Int. Conf, pp. 1-5, 6–9 June 2017.

[10] M. Khalil, “Markov process reliability model of PV inverter” 14th IMEKO TC10 Workshop Technical Diagnostics New Perspectives in Measurements, Tools and Techniques for system’s reliability, maintainability and safety Milan, Italy, June 27-28, 2016.

[11] A. Chappa, S. Gupta, L. K. Sahu and K. K. Gupta, "Resilient multilevel inverter topology with improved reliability,” IET Power Electron, vol. 13, pp. 3384-3395, Feb. 2020.

[12] A. Sarwat, P. McCluskey, Sudip K. Mazumder, M. Russell, S. Roy, S. Tufail, S. Dharmasena, and A. Stevenson. “Reliability Assessment of Grid Connected Solar Inverters in 1.4 MW PV Plant from Anomalous Classified Real Field Data,” 2022 North American Power Symposium (NAPS), 2022

[13] A. I. Sarwat, A. Domijan, M. H. Amini, A. Damnjanovic and A. Moghadasi, “Smart grid reliability assessment utilizing boolean driven markov process and variable weather conditions,” 2015 North American Power Symposium (NAPS), pp. 1-6, Oct. 2015.

References:

[14] A Khalilnejad, M. M. Pour, E. Zarafshan and A. Sarwat, “Long term reliability analysis of components of photovoltaic system based on Markov process,” Proc. SoutheastCon., pp. 1-5, 2016.

[15] Nikita Guptaa, Rachana Garga, Parmod Kumarb, “Sensitivity and reliability models of a PV system connected to grid,” Renewable and Sustainable Energy Reviews, Vol. 69, pp. 188-196, 2017.

[16] F. Lu, H. Zhang, H. Hofmann, C.C. Mi, “A Dynamic Charging System With Reduced Output Power Pulsation for Electric Vehicles,” IEEE Transactions on Industrial Electronics, Vol. 63, pp.6580-6590, 2016.

[17] A. Debnath, T. O. Olowu, S. Roy and A. Sarwat, “Voltage Regulation and Battery Stress-Reduction Strategy for DC microgrid,” 2021 6th IEEE Workshop on the Electronic Grid (eGRID), pp. 01-06, 2021.

[18] MIL-HDBK-217f, reliability prediction of electronic equipment, notice 2, 28 feb 1995.

[19] “Reliability Assessment of Critical Electronic Components,” RL-TR-92-1 97, AD-A256996.

Thanks for your attention