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Multi-Channel Networked MIMO-MPC-based SiL/HiL/MiL for CC/CV Sections' Optimization in 6th Gen Hybrid/Islanded Inverters for Mobile Green Nano-Grids in FEW Nexus

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Abstract: - The Food, Energy, and Water (FEW) Nexus is an ever-existing paradigm since the big bang. Resilient and mobile green energy nano-grid fabric is the horizon at the pinnacle of 6th generation inverters where FEW and major UNDP SDGs seem to meet. Three major challenges exist in the existing inverters: a) are based on uni-variable PID controllers and do not provide abstract grid parameters that make the decision-making for the consumers and OEMs, especially in islanded nano-grids; b) there is not a single MIMO-MPC-based solution that can employ a mesh network of spatially deployed Nanogrids nodes to derive the abstract key performance indicators (KPIs) in nano-grids, and c) the hardcoded smart inverters' firmware is impossible to optimize like SoC-based SiL/MiL/MiL looped embedded systems that hamper the adaptation of SISO-MPC and MIMO-MPCs. In this work design, development, and optimization of multi-channel CC/CV section modules based on MIMO-MPC using Hardware in Loop (HiL), Software in Loop (SiL), and Model in Loop (MiL) integrated 6th generation inverters architecture was proposed to achieve the autonomous green mobility nano-girds. The system achieved an efficiency of 7.8kWh/day at 20.8^{o} tilt with charging states of [23% to 65%].

Key-Words: - Energy, Power, Inverters, Grids

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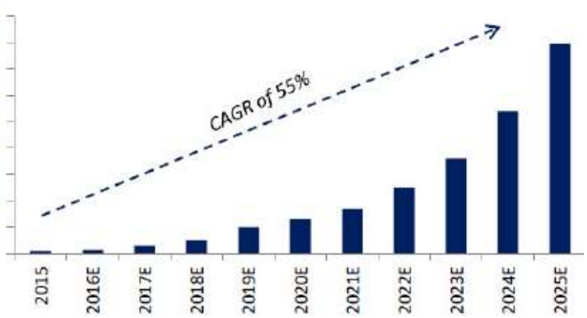
1 Introduction

The key motivation is improved quality of life and survival as a contribution to energy for FEW Nexus for global resilience and sustainability. Autonomy is an obligation for every industry and especially human survival which is a pressing need across the globe being UNDP SDPs 1-3, 6-9, and 11-15, mainly SDG-7 and SDG-9. Nanogrid's revenue will increase from $37.8 billion in 2014 to $59.5 billion in 2023 and Nanogrid business has the potential to radically change the power sector [1] as presented in fig 2 (a). According to Navigant, Europe now has the largest market for Nanogrids and is predicted to grow that market by 41.7% CAGR (compound annual growth rate) by 2024, going from 184.4 MW this year to 4,272.1 MW followed by Asia-Pacific with the expected installation of 5,619.9 MW installed in 2024, a 46.3% CAGR [2] as presented in fig 1.

a. Hybrid/Stand-Alone Inverter Market Shift



b. Green Nano-Grid Market CAGR

Fig 1. Expected Market Sizes of Nano-Grids and Inverters

The global inverter market is anticipated to grow at a CAGR of 15.7% from an estimated USD 16.3 billion in 2022 to USD 33.8 billion by 2027 [3]. The significance of multi-channel spikes by the global green energy share stats in 2021 (93 GW for wind and 133 GW for solar), renewable electricity generation grew steadily (+16% for wind and +23% percent for solar) [4]. The entire paradigm is expected to shift to green mobile nano-grids in coming years and can be a lifesaver for extremely poor countries that still don't have basic food, water, and energy, these drive extended research and optimization in this direction [5]. Even in space research, these gaps were addressed by the CubeSAT resilience concern [6].

2 Problem Formulation

The following gaps were found in existing nano-grid practices and orientation [7-9] literature regarding 6th generation inverters as shown in fig 2.

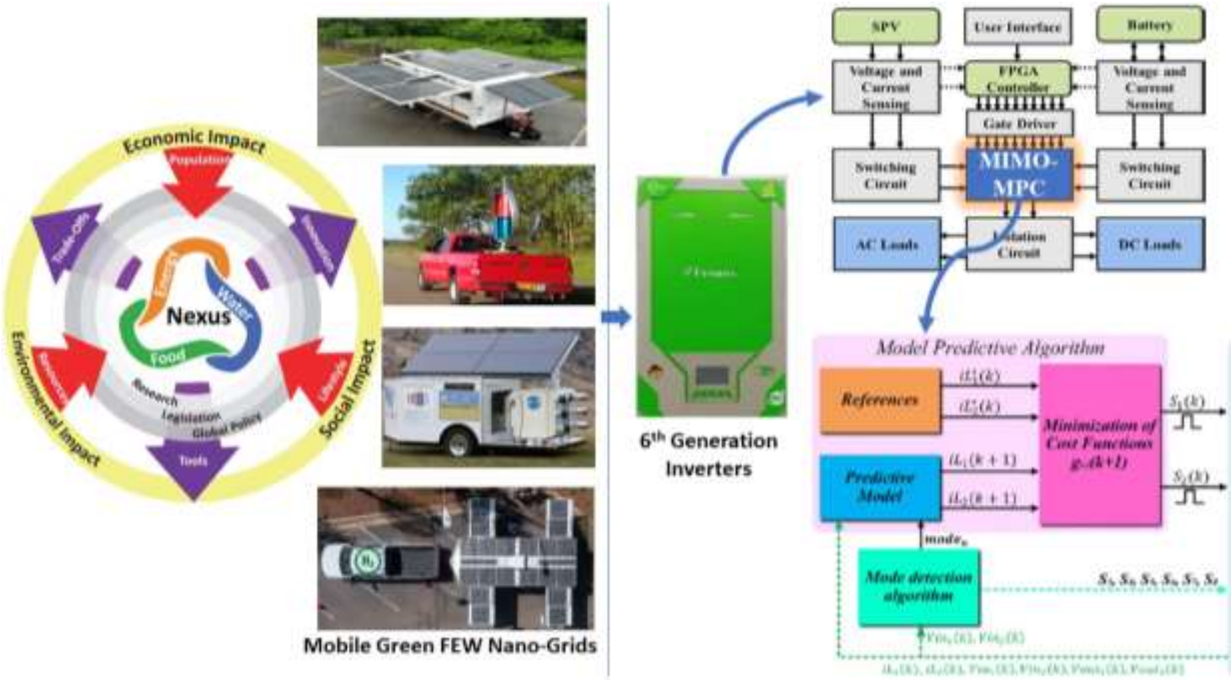


Fig 2. Overview of Research Gaps

In fig 1, a clear picture of the contribution expected from this research is presented and will have a huge impact on the green mobility-based FEW Nano-grids as a scalable factor in their future market. The role of electro-chemistry in conductors and energy elements and materials' structural health used is worth mentioning as per contributions [10, 11]. The nine potential gaps were observed in conventional PV inverters and are mentioned as:

a) There is not a single MIMO-MPC-based solution that can employ a mesh network of spatially deployed Nanogrids nodes to derive the abstract key performance indicators (KPIs) in nano-grids.
b) The existing inverters are based on uni-variable PID controllers and do not provide abstract grid parameters that make the decision-making for the consumers and OEMs, especially in islanded nano-grids.
c) The hardcoded smart inverters' firmware is impossible to optimize like SoC-based SiL/MiL/MiL looped embedded systems that hamper the adaptation of SISO-MPC and MIMO-MPCs as addressed energy harvesting [11] and the associated role of oxidation on the conductors [12].
d) Local nano-grids use a single channel approach, i.e. a single source of energy i.e., wind turbines or PV modules, and single storage type like battery types, and rarely have bi-directional AC/DC buses that are not a competitive candidate for 6th generation hybrid and islanded inverter applications as infrastructure concern [13, 14] and electrodes chemistry with pH issues [15].
e) The existing inverters systems have challenges in their parametric calibration (I/V/Hz, L, C, R, pF, %, Wh, Azimuthal Source Φ, Ψ, and θ tracking, geo (Latitude, Longitude, Altitude, and Windspeed) based generation, and forecasting) and operational adaptation that is a challenge in FEW mobile nano-grids and any islanded application.
f) The mentioned challenge (e) leads further to a lack of real-time resilience due to the absence of redundancy options in the mobility of smart systems [15]; ultimately energy professionals have to visit the sites that are challenging in harsh areas with electrode catalysis concerns [16] and remote locations due to the absence of remote power controller analytics.
g) Power/Energy scientists have a gap of awareness in instrumentation and control technology used in smart systems that effects the multi-variable systems integration in inverters due to the absence of Digital Twin in existing power converter-controllers as well

as their environmental impact and air quality issues [17, 18] and associated human health [19].

h) The programming, calibration, and remote access costs of the existing power converters systems are huge and complex methods like bipolar plates adaptation [20] challenge.

i) The existing power converter controllers have gaps in real-time analytics on-chip which is another setback costing the local consumers and problematic for subject matter experts (SME) that requires extra measuring instruments and secure interoperability [21-23] during control.

3 Research Methodology

A detailed literature survey for autonomous British energy systems, green mobility conditions, and food security constraints has been performed to streamline the critical energy-environmental variables and abstract parameters. The following research approach has been devised:

2.1 Survey of MIMO Bi-Direction Power Converters

The survey of the bi-directional MIMO power converters in section 1 devised the following directions:

- Magnitudes, frequency, location, and nature of AC/DC sources and converter topologies need to be studied and reviewed.
- Wind, PV/prime-mover, and multi-MPPT channel cascade with programmable DC bus options and control segments study.
- Utility, Genset, and prime-movers synching for programmable AC bus designs investigation.
- Multi-PIDs and MIMO control strategies for CV/CC equalization [24-27].
- Storage and buffering sources (batteries and super-capacitors) bi-directional conversion approach.
- Programmable DC-DC, DC-AC, AC-DC, AC-AC, and synching UPS configurations investigation.

2.2 Smart Power Converters KPIs:

Formulation of major KPIs to gauge the effect of MIMO bi-directional converters and their support for FEW services as a collaborative FEW-Grid Resilience Index (CFGRI) using the KPIs presented in works [28, 29] from the perspective of resilience in the energy efficiency of MIMO power drives communication systems.

2.3 System design

- The Selection of potential and stable sensors and controllers (with better outdoor life) for real-time measurement of variables and critical data processing procedures and statistical evaluations to compute real-time CFGRI [30, 31].
- Design of flexible/programable transformer-less smart converter with embedded IoT gateway system to achieve the required degree of autonomy by improved deep learning approaches for embedded IoT systems [32].
- Design and Model the multi-PIDs into MPC equivalents and implement them on the Smart Converters Topologies by validating on programmable power supplies [33].
- Design, Develop and Fabricate a Digital Twin with HiL/SiL/MiL Loop using Proteus, MATLAB, Physical System, and FEW Nano-Grid Test Bench.

The fault codes and digital calibration certificates (DCCs) using wireless consensus and temperature concerts for the entire deployment will also be taken into account based on the meteorological data as shown in the results section.

2.3 Measurement and Validation:

The developed system will be deployed in selected farms for measurement and data analysis.

2.4 Case Studies and Evaluation

The survey of the bi-directional MIMO power converters in following case studies.

2.4.1 Case Study 1

Static long-haul free-run in the geometrically classified field for stationery and mobile outdoor system evaluation over Digital Twin Test Bench (presented in fig 3).

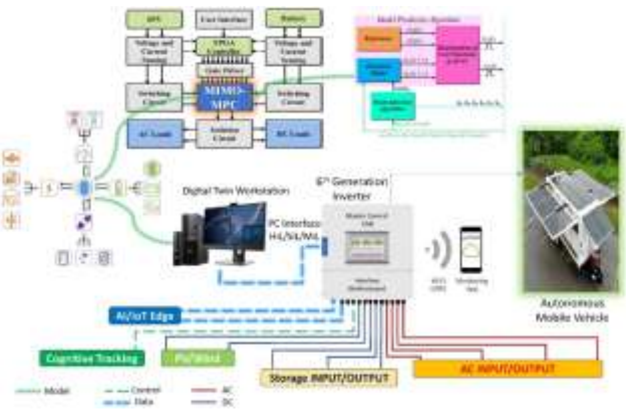


Fig 3. Complete System Implementation Layout with Case Study 1: Static Evaluation Test bench

2.4.2 Case Study 2

Mobile deployment for outdoor sensing and communication system evaluation for CFGI Mapping for geo-spatial evaluation ((presented in fig 4).

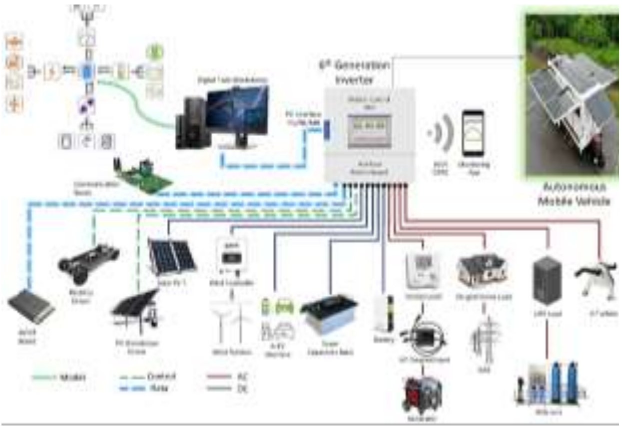


Fig 4. Complete System Implementation Layout with Case Study 2: Mobile Evaluation

In the second case study the 6th Generation Inverters Testbench will be installed on a Mobile EV and given a free run in outdoors to validate:

- A/V/Wh Generation Optimization based on Typography/Terrain.
- A/V/Wh Generation vs Autonomous Green Mobility.
- A/V/Wh Generation vs FEW Services.

Based on the outcomes of this research and developments in this research a startup company 1 will be initiated for 6th Generation Smart Inverters based hybrid and the Autonomous Mobile FEW Nano-Grid platform will be developed through a research grant leading to a startup company 2.

4 Results and Discussion

The system design spiking statistics are presented in a systematic manner from fig 5 to fig 10. Being a FEW based application the first step was the geographical site study using NMEA coordinates as mentioned in the problem statement.

Fig 5. Site Geography and Topography

The site chosen for simulation was Turaynah and its meteorological data was studied using online web data (https://qweather.gov.qa/CAA/Index.aspx) based on that data the irradiance study was performed for sun trajectories over the course of a year as shown in figure 6.

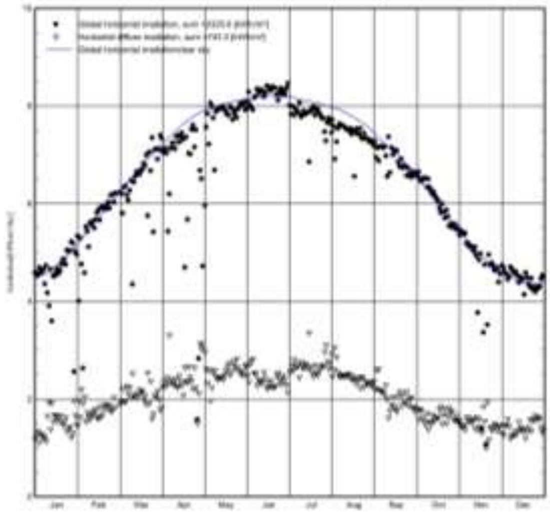


Fig 6. Site Meteorological Data

The next step in this FEW works was the clearness index study and its convolution with the sun hours and its path as presented in the figure 7.

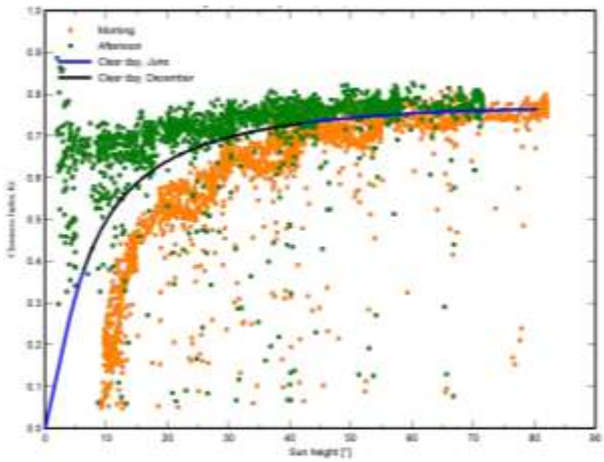


Fig 7. FEW-based Clearness Index for different positions of the sun.

As per the green block "cognitive tracking" in fig 3, it was mandatory to calculate the inter-shading effect of PV resources during the tracking process based on the sun height. For this, we used the cascaded shading mechanism inter-angular estimation presented in figure 8.

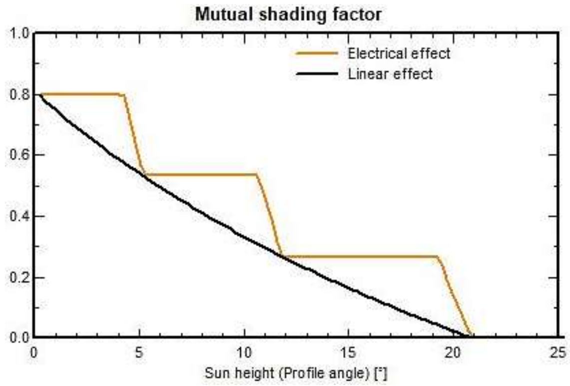


Fig 8. Inter-PV array shading estimation

The profile angle 20° can be observed in fig 8 for 0.8 deviation which is near optimal. After the static inter-shading effect, the dynamic tilting effect with transposition and irradiance was the major estimation required to estimate the impacts of tracking in the case of studies 1 and 2. In fig 9, it can be observed that the maximum shading loss of 1.7% was observed at 30° tilt which was a fraction of 45.5% of the annual energy profile for the same meteorological influx. In fig 9, pure transposition is expressed as a green curve, irradiation at 20.8° with black, and the for cell 15.6cm of 3 strings as orange curve.

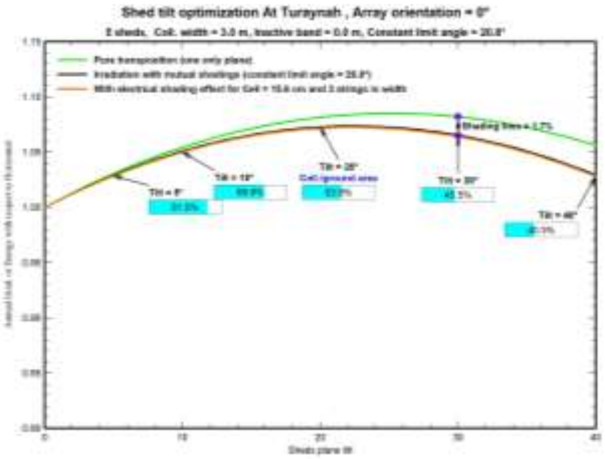


Fig 9. Tilt Optimization Estimation at 20.8° being an optimal fraction

The horizontal diffusion factor at 20.8° was estimated as optimal from 85° to 90° for sun height and with -90° to 90° and maximum on Jun 22 at 1:22 pm and can be seen the fig 10.

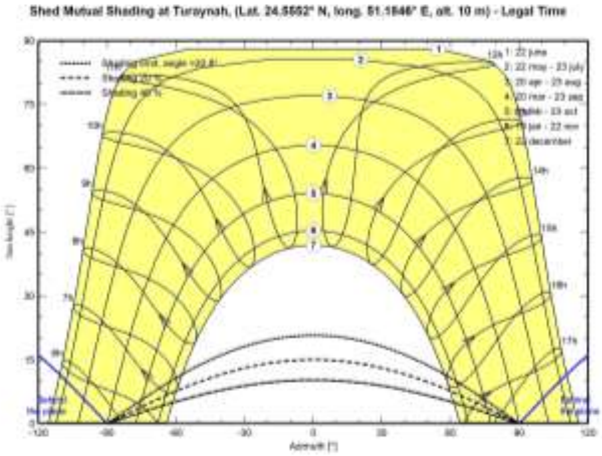


Fig 10. Mutual Shading and Horizontal Diffusion Estimation for 24 hours at 7 sun positions.

The PV efficiency was estimated using the 265W panel model in PVSyst with 6M-30S consisting of 60 cells and compliance 1000W/m^2 solar constant. The irradiance estimation for this model is presented for different irradiance conditions at 45° C temperature that varies the watts per m^2 from 200 to 1000. The maximum power generated by this using model was 242W at 28V and the minimum was 46.8W at 27V presented in figure 11. The values vary from location to location based on the meteorological data and tilt angles. In this study 20.8° tilt angle was used as the optimal power point.

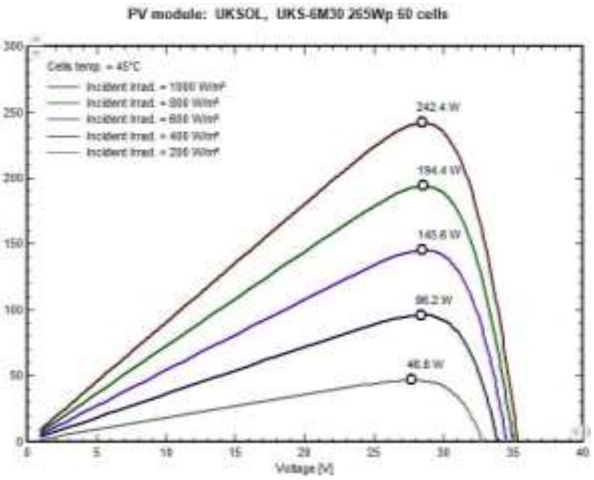


Fig 10. PV Module Power Estimation Simulation.

The step of individual PV module power estimation was the estimation of the complete PV system from Jan 1, 2022, to Dec 31, 2022, and is presented in figure 11.

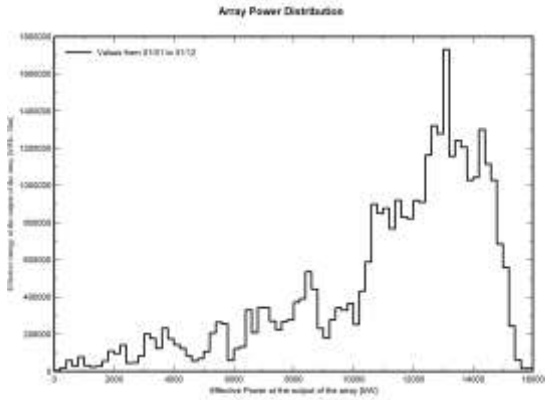


Fig 11. PV Array Power Distribution from Jan 1 to Dec 31, 2022.

In fig 11, it can be observed that the peak as MIMO-MPC based MPPT used in the system it touched the 1700.6MW using the per unit system kW/h energy unit standard. The state of charge for this energy magnitude was the next step as shown in the fig 12.

Fig 12. State of Charge for Battery Bank

In fig 12, it can be observed that the lowest state of charge was observed as 0.24 in the last week of January and the maximum was observed in the third week of June as 0.60+. In July the charging and discharging balance was observed, i.e. [0.63 to 0.41].

Fig 13. Daily Effective Energy output of FEW Nano-Grid

Before feeding the FEW Nano-Grid to any food or water service system the daily output efficiency estimation is the last step to conclude its productivity as a resilient energy alternative for food and water systems energy need services as shown in figure 13. This system can deliver an average of 7.3kWh per day with some exceptions in the last week of April and mid of November.

5 Conclusion

The presented research, system design, and simulation produced promising results as energy alternatives for FEW units. The electrical, mechanical, and meteorological variables were fed to the MIMO-MPC controller which helped in real-time estimations and computation of the SiL/MiL/HiL models. Such systems are expected to serve the energy needs of the food and water sector in a resilient manner as per the results presented. In the future we are planning to develop a cyber-physical MIMO-MPC 6^{th} generation inverter that can deliver the simulated results with certain variations.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Hasan Tariq proposed and designed the 6th generation PV-Wind hybrid inverters research.

Shafaq Sultan performed the simulation and results.

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