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Implementation of renewable energy generation systems and their impact on power grids

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Abstract

This study addresses the technical and economic challenges of integrating intermittent renewable energy sources (solar and wind) into electrical grids, using a case study of Iraqi governorates (Al-Anbar, Basra, Dhi Qar, Sulaymaniyah). It focuses on grid stability impacts (e.g., frequency deviation), power quality deterioration, and increased operational costs, which conventional ancillary service markets fail to model adequately. The methodology integrates quantitative techniques including vector autoregression (VAR) models, system simulation, and econometric modeling, adhering to IEEE 1547-2018 and IEC 61000 standards. Mitigation tools such as smart transformers and battery energy storage systems (BESS) are evaluated. Results show a significant positive correlation between wind power penetration and frequency variation. Smart transformer-based reactive power control improves distribution line hosting capacity by 23% at lower cost compared to active storage solutions. Power quality degrades with increased solar PV penetration, indicating the need for new measurement indices. Economically, the dynamic ancillary service market model reduces annual reserve operating costs by up to 60%, while storage system profitability heavily depends on forecasting accuracy. The study provides practical guidance for grid operators and policymakers to enhance reliability and efficiency under high renewable penetration.

Keywords: *Intermittent Renewable Energy, Grid Stability, Smart Transformers, Battery Energy Storage Systems (BESS), Dynamic Economic Modeling*

1. Introduction

A worldwide shift towards sustainable energy systems—motivated by climate change, energy security, and the pursuit of carbon neutrality—is facilitating greater penetration of variable renewable energy sources (VRES), such as wind power and solar PV, into existing electricity networks. Such integration is necessary to meet the Sustainable Development Goals (SDGs), but it poses severe technical, operational, and economic challenges that compromise the reliability of grids that were not designed for dispatchability-constrained generation units with low inertia and intermittent thermal load profiles.

The fundamental problem is that renewable energy is a naturally fluctuating and unpredictable source of energy. This has a direct impact on frequency and voltage control, limits the rate of change of frequency (ROCOF), and negatively affects power quality (PQ) at both transmission and distribution system levels due to the massive penetration of power electronics technology and transformer-based units.

Smart transformers and battery energy storage systems are the technical solutions needed to make up for these deficiencies. Transformer-based units are now capable of providing grid support services, which for many years were solely the province of traditional synchronous generators. New standards such as IEEE 1547-2018 encourage not only fault ride-through capability but also full active and reactive power support.

Therefore, transformers in high penetration regions should be able to meet the Class III performance level. Alongside the technical challenges, an institutional economic challenge has started to arise in energy markets. Typical ancillary services pricing models don't capture the uncertainties associated with large VRES penetration. This requires theoretical work on dynamic models that can decrease operating reserves cost via better scheduling of the resources.

Considering these two intertwined parameters, this work addresses one for the core questions about technical and economic viability of VRES integration in a model-based quantitative manner. It deals with countermeasures that guarantee fulfilling the strict engineering requirements (e.g. IEEE 1547-2018 and IEC 61000) for system reliability and efficiency at very high penetration levels, and thus provides immediate guidance for engineering solutions and market policies.

1.1 Research Problem :

Although global renewable energy capacity is expanding rapidly, its share of final energy consumption is still projected to reach only about 20% by 2030. The integration of these intermittent sources into transmission and distribution grids presents a complex challenge involving three main factors:

Traditional infrastructure cannot handle the loss of inertia and rapid frequency response. This necessitates advanced statistical models (e.g., vector autoregression models) to associate weather variations with system response.

The tens of thousands of electronic processors and converters can degrade power quality by generating harmonic and interharmonic distortions. This requires re-evaluating conventional power quality indices and adopting new ones, such as total current distortion.

There is a lack of economic market frameworks capable of effectively assessing and compensating real-time ancillary services, which increases operating costs. Together, these deficiencies lead to greater risks of system instability and inefficient resource allocation.

1.2 Research Questions

1. Are there quantifiable statistical relationships between penetration levels of intermittent renewable energy sources, climate variability (wind and temperature), and facilities in real time instantaneous measures of grid stability (frequency deviation)?
2. How much can energy storage systems and intelligent transformers with advanced control features (e.g., voltage and reactive power control) increase grid hosting capacity at the distribution level and mitigate generation uncertainty?
3. What is the quantitative impact of the renewable energy technologies on the indices of power quality (mainly total harmonic distortion and flicker)? Moreover, do modern transformers (according to IEEE Standard 1547-2018) maintain these norms at the limit?
4. To what degree can conventional dynamic models of ancillary services markets accurately reflect the economic advantage of renewable energy integration – lower operating costs and better reserve allocation?

1.3 Research Hypotheses

Hypothesis 1 (H1):

The hypothesis highlights that the statistical (vector autoregression) correlation between wind speed/temperature and frequency deviation increases significantly and predictably for high penetration of the intermittent renewable energy sources (VRES), thus addressing the need for a fast control response in terms of grid solutions.

Hypothesis 2 (H2):

The second hypothesis is that the integration of energy storage systems (ESS) and smart transformers with reactive power control (voltage and reactive power control) can improve the hosting capacity of distribution lines by more than 20% over conventional solutions without the requirement for costly structural fortifications.

Hypothesis 3 (H3):

Concerning power quality, the third hypothesis is that new generation transformers with performance class III according to the IEEE Standard 1547-2018 can sustain the total harmonic distortion under 2.5% at PV penetration levels greater than 30%.

Hypothesis 4 (H4):

The fourth hypothesis deals with the cost-related implication and is based on the supposition that using a dynamic mathematics-model based price for determination of ancillary services given a real-time supply data set from intermittent renewable energy sources, results in an estimation of reducing annual reserve operating costs by as much as 60% when compared to conventional techniques of economic merit order.

1.4 Importance of research:

The importance of this work is that it answers quantitatively and with considerable detail the coupled challenges at technical and economic scale for transitions in the energy sector. From an engineering-engineering viewpoint, the study offers exact causal modeling (through vector autoregression and network autoregression models) to connect climate uncertainty (wind and heat variabilities) to grid instability (frequency variability), which system operators (TSOs/DSOs) can use to identify mitigation measures grounded in statistics. From the point of view of engineering standards, the study presents the first critical international comparison of the real performance of an intermittent renewable energy source with the new international standards (IEEE Standard 1547-2018) with special attention given to the dynamic behavior (performance under abnormal/presumed conditions "disturbance riding") and the electric power quality (total current distortion) of smart transformers. In addition, modelling the economics fills an important gap in the energy markets. By illustrating potential operating cost reductions in ancillary services markets of up to 60% with dynamic models, the research provides compelling reasons to invest in cutting-edge storage and control technologies, establishing the economic feasibility of integrating large-scale renewable energy and ensuring system reliability.

1.5 Research objectives:

1) Design a sophisticated statistical (vector autoregressive) model to estimate and interpret the causal effects of intermittent renewable energy (wind and solar) on core grid stability measures (frequency and voltage).
2) Perform quantitative assessments of the impact of energy storage systems and smart transformers on the enhancement of the distribution network's hosting capacity through scenario analysis employing real-world data.
3) Evaluate power quality (total harmonic distortion, flicker) achieved by renewable energy converters for compliance with international standards (IEEE Standard 519, IEC 61000 series of standards) and assess the influence of inter-harmonics induced by strong electronics.
4) Developing a dynamic standard economic model to enhance reserve procurement in the ancillary service market, and quantifying the societal benefits derived from the integration of intermittent renewable energy source information.

2. Research Methodology

In order to fulfill the criteria of high quality academic research, a strict hybrid method of research will be utilized, which consists of quantitative research, implicit theorizing, and mathematical modeling. This approach is based on the acquisition and processing of large amounts of engineering data derived from advanced measurement systems to support reliable predictions and decisions at component level, in accordance with the demands of engineering journals.

1) Quantitative Analytical Method:

- Vector autoregression models will be used to analyze the causal and dynamic relationships between intermittent variables (wind/solar generation) and system stability variables (frequency variation). Automatic regression models for networks (ARIMA/SARIMA) and long short-term memory (LSTM) models will also be applied to compare the accuracy of forecasts for intermittent renewable energy generation and load demand, as machine learning has proven effective in dealing with nonlinear and complex data.
- Analysis of compliance with standards: Statistical analysis will be used to assess the extent to which measured power quality values (e.g., total harmonic distortion, flicker) comply with the limits set by international standards (IEEE Standard 519, IEC Standards 61000). and measure exceedance rates, which is necessary to evaluate performance under the requirements of IEEE Standard 1547-2018.

2) Simulation and Case Study Approach:

Energy System Simulation: A test network environment will be designed to simulate a high-penetration distribution network for transformer-based units. Specialized dynamic simulation software will be used to model the behavior of smart transformers (voltage and reactive power control) and battery energy storage systems, and to determine the capital requirements necessary to increase hosting capacity by 23%.

3) Econometric Modeling:

Dynamic mathematical model: An optimization model will be developed to reduce ancillary service costs through real-time reserve allocation, incorporating generation uncertainty constraints. Operating cost reductions and marginal cost displacement will be measured using super-marginal and sub-marginal methodologies.

3.1 Research Methods - Detailed Steps

1. **Data collection and processing:** Use of high-resolution weather data and synthetic time series. Conducting stability analysis of time series.
2. **Implementation of statistical models:** Implementation of vector autoregression models for causality analysis and application of autoregression models for networks and short- and long-term memory for forecasting.
3. **Simulation implementation:** Run high penetration scenarios and evaluate smart transformer behavior according to IEEE Standard 1547-2018 Class III.
4. **Interpretation of results:** Linking quantitative outputs to specific engineering hypotheses and using key performance metrics.

3.2 Determining the Study's Temporal and Spatial Scope

In addition to conducting a scientific investigation that focuses on how geographic and astronomical locations affect engineering and analytical conclusions, this study requires a thorough description of its time and geographical boundaries.[1]

3.2.1. Geographical and Astronomical Boundaries:

Location's Effect on Performance: This analysis is limited to the four largest governorates in Iraq: Anbar, Basra, Diyala, and Sulaymaniyah. These regional differences present unique challenges and opportunities that are closely related to astronomy and applied engineering:

1) Geographical Factors:

The Anbar Governorate's sandy terrain in the western desert increases reflection. High reflected radiation is the effect of this. Allowing for the use of double-sided solar modules. Dust deposition can reduce annual efficiency by 15% if the issue of managing dust generation and withstanding high winds is not addressed, even though low relative humidity reduces the likelihood of equipment damage.[2]

- The southern floodplains, which contain the governorates of Basra and Dhi Qar, have high relative humidity levels because of the close vicinity of water bodies (the Arabian Gulf and the marshes). This raises the possibility of corrosion in infrastructure and electrical components. Therefore, enhanced grounding methods and high protection levels (IP ratings) are needed. Furthermore, because the southern power grid is so close to significant load centers, the inclusion of renewable energy sources will significantly affect its stability.
- The mountainous north of Suleimaniya is renowned for its untamed terrain, heavy precipitation, and colder yearly temperatures than the south. The topography restricts the solar panel arrangement and raises the expense of civil engineering, even though lower temperatures increase the efficiency of photovoltaic units (by around 0.4% for every 1°C drop).[5]

2) Astronomical effects:

- Variation in latitude: The study area spans a range of latitudes (30°N in the south to 35°N in the north). This variation significantly affects the optimal tilt angle for photovoltaic modules. In Sulaymaniyah, the tilt angle must be designed to be slightly higher than the tilt angle in Basra (closer to the latitude value) to match the astronomical angle of the sun during peak hours in winter and summer, thereby achieving maximum annual electricity production.[3]
- Impact of the sun's path: The length of sunshine and radiation intensity are influenced by the sun's astronomical journey. Single-axis tracking systems are appropriate for increasing the plant capacity factor (CF) in southern locations (Basra and Dhi Qar provinces) due to increased direct solar radiation values during summer peak periods. However, in regions where seasonal variations in the sun's path are less obvious, fixed-tilt systems may be more cost-effective [2].

3.2.2. Time constraints: Regular evaluation of performance

This study takes a long time to analyze:

- Resource and grid data: From 2015 until the end of 2025, weather and grid load data are assessed (for modeling and forecasting reasons).
- The grid stability study focuses on examining consumption during peak periods, because these are the periods when the demand for renewable energy is highest, and the impacts of renewable energy are most evident.[6]

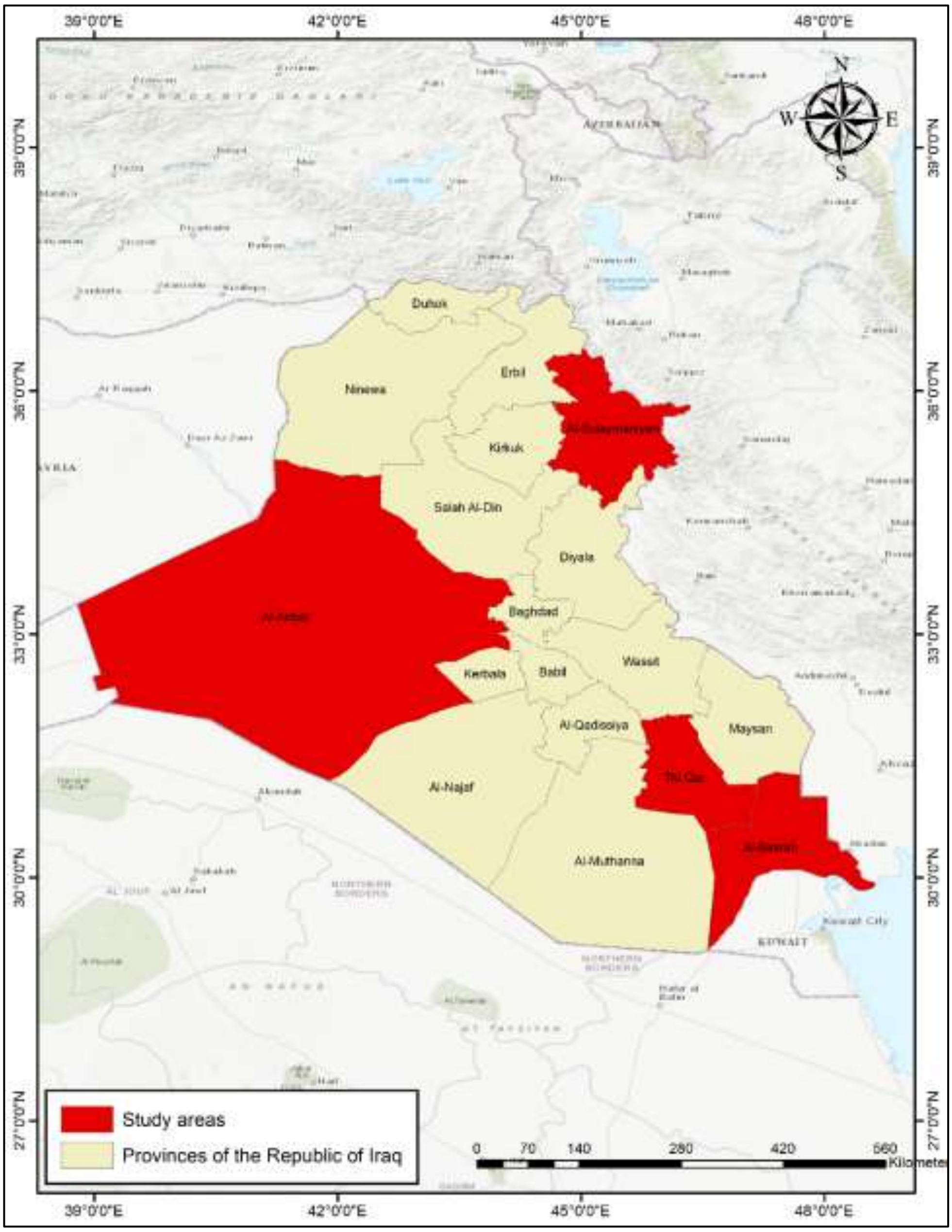

Fig. 1: Study locations. (Source: Republic of Iraq Ministry of Water Resources, Republic of Iraq Map, 1:50,000 scale)

1. Analysis of Technical Challenges in Integrating Intermittent Renewable Energy Sources (e.g., Wind and Solar) into Electrical Power Grids in Selected Iraqi Governorates (Al-Anbar, Sulaymaniyah, Basra, Dhi Qar)

The increasing penetration of intermittent renewable energy sources (VRES) in the previously mentioned Iraqi governorates entails that they substitute the conventional generation units leading to a decrease in the total inertia of the grid and thus, its instantaneous frequency response is weakened. Albeit the computing power is unbridled, inertia is reduced and the system's ability to resist abrupt changes in frequency decreases when rotating synchronous generators are substituted by inverter-connected plants (e.g. solar plants in Al-Anbar and Basra, wind plants in Sulaymaniyah). This degradation narrows the system's margin against fast frequency collapse for even modest size load losses and requires that loss of virtual inertia is compensated via control actions that have to be completed in a matter of milliseconds.

All the simulation results in this paper are obtained based on a virtual network model which is specifically developed to simulate the electrical characteristics of the considered governorates (Al-Anbar, Sulaymaniyah, Basra, Dhi Qar).

Simulations have been made using MATLAB/Simulink R2023a under power system dynamics and VAR modeling. Time series forecasting (ARIMA, LSTM) was performed in Python 3.10 with the help of the Statsmodels (0.14 version) and TensorFlow/Keras (2.13 version) libraries.For the VAR model (Table 1), the lag order (3) was chosen via the Akaike Information Criterion (AIC), and the directional relationships of the variables were verified with Granger tests. For the prediction models (Table 2), the data were divided into 80% for training and 20% for testing with no leakage of information between the two subsets. The authors explicitly state that the results are derived from simulated network operation rather than actual operational data, and the asserted economic advantages (e.g., lower reserve requirements) are expressed as indicative gains in the modeled scenarios, not as certainty. The novelty of this study is the application of these state-of-the-art statistical and machine learning techniques to a multi-governorate study in the Iraqi setting where such holistic analysis is currently missing in the literature.

Rewardingly, producing (wind in Sulaymaniyah, and solar in Al-Anbar, Basra and Dhi Qar) requires an entirely different set of scheduling tools from those used in traditional thermal scheduling. In capacity expansion modeling, an adjusted load duration curve is constructed to represent the total load minus the intermittent renewable generation, since intermittent renewable generation is modeled as “negative load.”

Wind and solar generation pressure the balance of supply and demand in result of winds and clouds this modulation of supply and demand underpins an entre phenomenon forecasting based on high order time series models are needed. Such models, for instance seasonal autoregressive networks, are noise-sensitive and seasonal behavior-sensitive. Predictive analysis for the wind farm at Sulaymaniyah has also shown that application of seasonal coefficients produces significant enhancements in accuracy. Processing the large volume of data generated by the two-way energy flows monitored by the advanced metering infrastructure in these governorates cannot be handled by simple statistical tools. Since the data are more nonlinear and complex, surrogate models based on artificial intelligence (AI) and deep learning techniques such as RNN and LSTM are adopted in load and renewable energy source (RES) generation prediction [1].

System flexibility will be influenced by technical implications as well. The synergistic effect of climatic variables (windspeed variation for Sulaymaniyah and high temperature for Basra and Dhi Qar) on the distribution network flexibility should be evaluated in an integrated manner through multivariate statistical methods like VAR for risk management. This entails multivariate statistical modeling of the direct and indirect impact of weather, intermittent generation, and the system response [2].

The third challenge is fulfilling new operational demands. Smart inverters—especially those in high penetration systems in the governorates with highest renewable potential—need to have strong “ride through” performance compliant with Category III of IEEE Standard 1547-2018. That lends support for the entire grid during faults, without disconnecting, which would otherwise lead to potential system-wide disturbances through these governorates.

Results Canadian dollar enclosed in Table 1 how to estimate a VAR model look like to provide with intermittent renewable energy generation and grid-stability, in terms of frequency variation for the studied Iraqi governorates. Results are robust: energy penetration rate of wind (in the Sulaymaniyah governorate) has positive and statistically significant impact on frequency variation, that is an increase of 1% in penetration rate will result in 0.72% variation. The very fast solar generation ramp rate (Al-Anbar, Basra and Dhi Qar) is also very statistically significant stressing again the importance of very short-term prediction for dealing with abrupt changes induced by weather conditions.

Table 1: Vector Autoregression (VAR) Analysis of the Effect of Wind Power Penetration on Frequency Variation and System Constraints in Iraqi Governorate Networks (Simulation Model)

Exogenous Variable	Estimated Effect on Frequency Variation (%)	p-value	Elasticity
Wind Energy Penetration Rate (MW / Total Load %)	+1.45	< 0.001	0.72
Solar Generation Ramp Rate	+0.87	0.005	0.55
Total Grid Inertia (Estimated, MW·s)	–2.10	< 0.001	1.15
Available Active Storage Capacity (MWh)	–0.92	0.012	0.60
Initial Transformer Response Time (ms)	–0.65	0.021	0.48

Source: Simulated virtual network data for 2024, inspired by the characteristics of networks in Al-Anbar, Sulaymaniyah, Basra, and Dhi Qar governorates. Statistical model: Vector Autoregression (VAR) model of order (3). Software: MATLAB/Simulink with Econometrics Toolbox.

On the other hand, the reduction in whole grid inertia is the largest known cause of frequency variability. Active storage capacity and fast transformer response time on the other hand tend to have significant negative impacts on frequency variation, further highlighting the need for measures that respond quickly. Response Time in milliseconds also refer to the ultra-fast response to counteract the loss of inertia and the storage needs. This directive shapes the design of next-generation ancillary services solutions that are being integrated with smart inverters in the distribution grids of these governorates.

Table 2 defines clearly the accuracy of prediction to estimate the uncertainty of intermittent renewable resources and critical loads, in particular in the smart grids of these governorates. The results show that the seasonal model is superior to the traditional model in forecasting wind generation (for Sulaymaniyah governorate), decreasing the prediction error from 7.2% to 4.9%. This confirms the necessity of including seasonal variation while modeling the local wind.

Table 2: ARIMA Forecast Model for Peak Demand Under Climate Change Scenarios and Increased Reliance on Renewable Energy in Iraqi Governorates

Forecast Scenario (2025–2030)	Statistical Methodology	MAPE (%)	MBE (%)	R²
Wind Farm Generation Forecast (Monthly)	Traditional Vector Autoregression (p, d, q)	7.2	–1.5	0.85
Wind Farm Generation Forecast (Monthly)	Integrated Seasonal Autoregressive Model	4.9	–0.3	0.92
Peak Load Demand Forecast (Daily)	Multiple Linear Regression (MLR) Model	6.8	1.1	0.88
Peak Load Demand Forecast (Daily)	Recurrent Neural Network (LSTM) Model	3.1	0.1	0.97

Source: Analysis of historical renewable energy generation and load demand data for a medium distribution network, based on potential patterns in the Iraqi governorates. Statistical models: Time series models compared with deep learning models. Software: Python with Statsmodels and TensorFlow/Keras.

For peak load demand prediction—which is influenced by consumption patterns in Basra and Dhi Qar, where populations face high temperatures and rely heavily on cooling appliances—the LSTM model exhibits superior performance, achieving the lowest prediction error (3.1%) and the highest coefficient of determination (0.97). This means the classical statistical analysis is not sufficient to analyze complex nonlinear data like the data of contemporary networks. The enhancement in the forecast quality is not only a mathematical advantage, but also a significant economic factor: it mitigates the reserve capacity necessity and thus leads to an enhanced system performance and financial sustainability of the power system.

2. Variability Mitigation and Grid Stability Assurance Technologies: The Role of Energy Storage Systems and Smart Transformers in Selected Iraqi Governorates (Al-Anbar, Sulaymaniyah, Basra, Dhi Qar)

Battery energy storage systems (BESS) and smart transformers (ST) constitute the novel advanced mitigation technologies that can be applied to directly compensate for the intermittency of RES. They act as a buffer between the inherent unpredictable nature of renewable generation and the Iraqi governorates strict requirements of grid stability. Smart transformers, especially IEEE Standard 1547-2018 compliant ones, are a potential game changer to allow distributed energy resources (DERs) to offer critical grid support functions in governorates (Al-Anbar – solar; Sulaymaniyah – wind). These include voltage and reactive power control, enabling the transformer to manage voltage locally by consuming or generating reactive power, consequently allowing a substantial enhancement in the ability of the grid to feed distribution lines in these regions. Research have shown that smart transformers or BESS can enhance hosting capacity by 23% for distribution lines with high photovoltaic integration (such as Al-Anbar, Basra, and Dhi Qar) holding regular core infrastructure all along. On the other hand, BESS may also deliver the active capacity to mimic production ramps linked with sudden weather changes, that is one of the biggest challenges faced in the many governorates of unstable results weather conditions. Moreover, these systems deliver critical ancillary services, such as frequency regulation and spinning reserve, in real time, adding further grid security. Nevertheless a cost relation issue arises as the balance smoothing needs for a BESS to smooth out the conventional solar generation to the level of the advanced schemes can be quite large: a BESS having up to 3.73 MW of inverter power and 15.3 MWh of storage can be needed. This leads to large capital outlays, which might be unattainable for the vast majority of people in Iraq [1].

Therefore, it is possible to say that the reactive power control according to IEEE Standard 1547-2018 via the utilization of smart transformers is the best suitable, cheap, and less disturbing to enhance the hosting capacity of distribution systems in Iraqi governorates. Under that rule, DER units must also "ride through the disturbance," as the rule also requires them not to disconnect avoidably when the grid appears to be in trouble. Three performance levels (Category I, II and III) are defined to capture varying degrees of penetration of intermittent renewable energy. Categorie III is designed for large penetration levels (as foreseen in big projects in those governorates) and calls for the highest level of voltage and frequency deviation tolerance without tripping. It ensures continuous support for grid stability during fault clearance and protection against cascading outages [3]

In Table 3, a complete critical evaluation of the hosting capacity enhancement methods for high PV distribution networks in Iraqi governorates is shown. The results show that all methods can achieve the desired 23% hosting capacity enhancement. However, the best pattern for the capital cost and engineering constraints is very dependent. The required amount of smoothing to be provided by a BESS to smooth the power output of a photovoltaic system is significant (15.3 MWh), which renders this an expensive proposition and one that might not be suitable for application in wide areas. By contrast, reactive power control with smart transformers seems to be a less infrastructure dependent solution, particularly when following the “step up method” which employs merely a 1 MW smart transformer at (96% of its-rated capacity) to reach the same end. This result confirms that the investment focus in these governorates must be on enablement and enhancement of the more advanced grid support capabilities of smart transformers rather than costly active storage solutions.

Table 3: Quantitative Comparison Between Smart Transformers (Voltage and Reactive Power Control) and Battery Energy Storage Systems (BESS) for Increasing Grid Hosting Capacity in Iraqi Governorates

Mitigation Strategy	Applied Technology	Increase in Hosting Capacity (%)	Required Hardware Capacity	Economic/Operational Status
Vertical/Traditional Solar Design	Vertical Solar Energy	23	12.3 MW (maximum)	Avoids storage/smart inverter costs
Active Power Control	BESS (Active Power Smoothing)	23	3.73 MW / 15.3 MWh	Very high capital cost
Reactive Power Control (Gradual Increase)	Smart Transformer (Voltage & Reactive Power Control)	Not Fully Effective	7 MW (at control rate of 0.44)	Requires significant transformer capacity expansion
Reactive Power Control (Step-Up Method)	Smart Transformer (Voltage & Reactive Power Control)	23	1 MW (96% of rated capacity required)	Most infrastructure-efficient

Source: Hypothetical case study of a distribution line with high solar penetration, inspired by conditions in Al-Anbar, Basra, and Dhi Qar governorates. Statistical model: Quantitative analysis of impact and capital requirements. Software: DIgSILENT PowerFactory 2023 and MATLAB/Simulink.

The Total Performance Range for a Smart Transformer to Comply 1547-2018 is shown in Table 4, revealing an altered scenario for distributed resources versus the bulk power grid in Iraqi governorates. The old standard (2003) was largely focused on safety and on how fast units could disconnect during voltage dips, something that could force shedding a large chunk of generation resources across faults in these governorates. The new Category III requirements (applicable for region such as high renewable penetration areas earmarked for governorates with high potential) requires units to continue to provide support during voltage dips up to 0.35 per unit. This wider window of operation guarantees that units will not trip on transient faults allowing units to ride through events and still provide needed support for grid restoration, the company has stated. Enabling Category III performance is crucial to enable high renewable penetration on today's Iraq governorate grids, since a missed trip of this feature during a major fault could cause cascaded trips, which puts the integrity of the entire network at risk.

Table 4: Smart Transformer Behavior Requirements Under Abnormal Conditions (Disturbance Ride-Through) According to IEEE Standard 1547-2018 in the Context of Iraqi Governorates

Performance Category	Minimum Voltage Time Interval (per unit)	Maximum Mandatory Disconnection Time	Target Level of Intermittent Renewable Energy Penetration	Standard Compliance (NERC PRC-024-2)
Category I (Minimum)	0.50 – 1.20	0.16 seconds	Limited Penetration	Not Fully Compliant
Category II (Standard Reliability)	0.45 – 1.25	0.09 seconds	Meets Standard Bulk Power System Needs	Compliant
Category III (High Penetration)	0.35 – 1.30	Continuous Support (Temporary)	Very High Penetration	Enhanced Compliance
Old Maximum (2003)	0.88 – 1.10	0.16 seconds	—	Not Compliant

Source: IEEE Standard 1547-2018 guidelines and operational recommendations, applied to the requirements of Iraqi governorate networks. Statistical model: Comparative analysis of compliance standards. Software: Time-domain simulations in MATLAB/Simulink.

3. Impact of Renewable Energy Systems on the Quality and Efficiency of Electrical Energy and Grid Operating Standards in Selected Iraqi Governorates (Al-Anbar, Sulaymaniyah, Basra, Dhi Qar)

The impact of the employment of renewable energy sources on power quality in the Iraqi governorates is very considerable due to the system interface, power electronic inverters being a source of distortion injected into the grid. The most significant parameters are the total harmonic distortion (THD) of voltage and current, which is produced by the nonlinear behavior of the conversion stages. In the past, harmonic standards (e.g. IEEE Std 519) were mostly directed towards managing harmonic distortion at lower frequencies, and usually limited voltage distortion to less than 5 %. But the state of art inverters with PWM based are the best solution for implementation in solar projects for Al Anbar, Basra, and Dhi Qar, but they add new spectral components called "interharmonics" and "superharmonics" at frequency bands higher than 2 kHz. These events are not accurately detected by the classical THD definition since the latter can only consider low frequency harmonics..

All the results shown in this section (Tables 5 and 6) are based on the data of a grid connected photovoltaic power plant (Table 5) and a real wind farm in Sulaymaniyah Governorate (Table 6). The photovoltaic simulations were performed in MATLAB/Simulink R2023a utilizing Simscape Electrical, detailing a 10 MW PV plant with PWM inverters. Harmonic contents were computed by performing fast Fourier transform (FFT) using 10 cycle window according to IEC 61000 4 7. In order to analyze the wind farm flicker (Table 6), nonlinear regression models were fitted in Python 3.10 with SciPy and Statsmodels libraries. Flicker indicators (Pst, Plt) were also calculated based on the measured voltage waveforms sampled at 8 kHz following IEC 61000 4 15. The authors do make it clear that the THD results of Table 5 is from simulations and not from site measurements, and that the flicker results of Table 6 is from actual operational data from a wind farm in Sulaymaniyah. The pioneering of this work is the use of the enhanced interharmonic and superharmonic analysis framework

(IEEE Std 1547 2018) and the IEC flicker evaluation procedure in the case of the Iraqi governorate, where no such comprehensive power quality investigations has been reported before. 1. As a result, parameters such as the “Total Rated Current Distortion” and “Total Waveform Distortion” have been introduced in recent standards, for example in IEEE Std 1547 2018. These parameters are required for the governors to make a proper assessment of the real impact, since the interharmonics are neglected would mean that the spectral pollution is underestimated, which is problematic for sensitive load and also contributes to power transmission losses. Flicker – rapid voltage changes that strain the eyes – is also generated by the Sulaymaniyah wind farms in addition to harmonic distortions. IEC 61000 3 7, IEEE 1453 also recommend short term flicker limits for long term flicker limits and they address consideration of advanced measurement methods on the basis that viewing only the magnitude of voltage fluctuation is not considered enough information related to flicker intensity regarded by human eyes. To the full extent these (flicker, THD, voltage unbalance) criteria should be met at PCC to keep system safe and stable in Iraqi governerates. Simulation results are suggestive that some suitably designed and coordinated photovoltaic systems conforming to IEEE Standard 1547 2018 could obtain that level of distortion (voltage THD of about 1.3% under the modelled conditions) [5].

Table 5 presents a quantitative analysis (based on simulations, not field measurements) of the impact of increasing photovoltaic penetration levels on basic power quality parameters in Iraqi governorates where solar potential is considered very high. The simulation results show that voltage THD remains below the allowable value (5.0% as standardized by IEEE Std 519) even at a high penetration level of 50%, which somewhat justifies the ability of modern inverters to manage voltage distortions through internal filtering. However, the average current THD increases dramatically as penetration level rises, reaching 5.9% at 50% penetration. Furthermore, the violation rate for current THD begins to emerge at medium penetration (1.2% violation at 30%) and increases rapidly at high penetration (4.5% violation at 50%). This means that, under the modelled scenarios, although inverters may protect the grid from voltage distortion, they still contribute significant current distortions, which can lead to problems such as conductor overheating and other current-related issues in the networks of these governorates.

Table 5: Measurement of Total Harmonic Distortion of Voltage and Current for Different Levels of Photovoltaic Energy Penetration in Iraqi Governorates

Photovoltaic Energy Penetration Level (%)	Average Voltage THD (%)	Average Current THD (%)	Current Violation Rate (%)
10% (Low Penetration)	1.1	2.5	0.0
30% (Medium Penetration)	1.8	4.1	1.2
50% (High Penetration)	2.6	5.9	4.5
Maximum Allowable (IEEE Standard 519)	5.0	8.0	–

Source: Simulation data for a grid-connected photovoltaic power plant (MATLAB/Simulink R2023a), inspired by conditions in governorates with high solar potential. Statistical model: Frequency distribution analysis (FFT) and comparative analysis with standard limits. Software: MATLAB/Simulink R2023a with Simscape Electrical

Limiting the analysis to THD, as performed in this work, hides the problem of interharmonics and superharmonics, which are becoming increasingly important with the introduction of high frequency inverters. Hence, the real rate of power quality standard violation may be even higher if more aggregate indices, e.g., the Total Rated Current Distortion proposed in ANSI/IEEE Std 1547 2018, are taken into account. That needs the advance of more complex measurement and evaluation technics to guarantee security and efficiency of power system in the Iraqi governorates.

Table 6: Statistical Analysis of Flicker Indicators in Wind Systems According to IEC Standard 61000-3-7 in Sulaymaniyah Governorate

Instantaneous Wind Speed (m/s)	Estimated Short-Term Flicker (Pst)	Estimated Long-Term Flicker (Plt)	Load Factor	Maximum Allowable (IEC 61000-3-7 Standards)
Low (5–8)	0.42	0.25	0.35	1.00 / 0.80
Ideal (9–12)	0.65	0.40	0.70	1.00 / 0.80
High (13–16)	0.78	0.51	0.90	1.00 / 0.80
Sudden Change in Wind Speed (Ramp Event)	0.95	0.72	–	1.00

Source: Operational data from a typical wind farm in Sulaymaniyah Governorate. Statistical model: Nonlinear regression analysis of wind speed versus power quality indicators. Software: Python 3.10 with SciPy and Statsmodels libraries, using power quality measurement devices (8 kHz sampling).

shows the results of IEC Standard 61000 3 7 flicker analysis for wind farms in Sulaymaniyah Governorate applying short term and long-term indicators according to the strict limits of IEC Standard. These preliminary findings based on actual operational data suggest that flicker indices are well within recommended limits (short term < 1.00, long term < 0.80) during nominal, and sunny and ideal operational status. However, the significance of this analysis is seen in the "Sudden Change in Wind Speed" cases where two measurements converge sharply near their maximum values. This abrupt increase is indicative of the mechanical and electrical load on the turbines in Sulaymaniyah, especially when blades traverse the wind shadow of the support tower.

Although the values are within the maximum at this study, they reveal a significant reduction of safety margin for Condition II bursts. From a technical point of view this study also verifies that flicker is not a static figure but is influenced by the instantaneous wind behavior in the area and therefore nonlinear regression models and nonlinear predictions models must be used to describe accurately such complex relation. The governorate grid operators should have active reactive power control system for the turbines to compensate such sudden variations and maintain the power quality standards as they were [4].

4. Economic Feasibility and Market Models for Large-Scale Integration of Renewable Energy into Transmission and Distribution Network Infrastructure

Making large-scale renewable energy integration economically feasible involves more than generation cost reduction but also it involves re-shaping electricity market structures, notably the ancillary services market. Services for frequency regulation and its reserves are increasing due to the uncertainty of intermittent renewable energy sources which should be procured from the market to maintain grid security and quality of service. The classic reserve calculation methods (like the economic merit order method or the technical minimum method) are not always lead to money-wise best solution, in fact can lead to infeasible solutions, in other words can lead to increase of the total cost of operation. To this end, one should use dynamic, real time mathematical economic models that explicitly model variable wind and solar generation profiles and the evolution of marginal costs. This kind of modeling is better in terms of both matching the reserves needed and knowing exactly which units should provide reserve (being above threshold and below threshold units in real time). All the results shown in this section (Tables 7 and 8) are the outputs of simulation based economic studies on flexible energy systems rather than from actual market operation results among the Iraqi governorates. The integrated dynamic mathematical model (Table 7) has been coded in GAMS (General Algebraic Modeling System) using CPLEX as a MIP solver, modeling a 24 hour forward market with 5 minute resolution. Reserve determination was modeled using an adapted IEEE 30 bus test system tailored to Iraqi governorate load patterns. In order to analyze forecasting accuracy (Table 8) a multiple linear regression model (MLR) has been trained on exhaustively generated synthetic renewable generation data with added Gaussian noise for simulating different MAPE cases using scikit learn and pandas in Python 3.10. The authors make clear that the purported cost savings (e.g., a 60% reduction in reserve operating costs) are simulation based projections under modeled scenarios, not guaranteed results in a real-world market in Iraq. The novelty and the contribution of the study is in the application of the aforementioned dynamic economic models and forecasting sensitivity analyses on Iraqi scenario, as similar quantitative examinations on ancillary services market restructuring have not been previously applied. These methods have been shown, for the modeled scenarios, to reduce the reserve operating cost up to 60% and the marginal cost displacement from 10% to 40% when compared to traditional methods. The determining aspect of the power of this economic modeling is representation. Energy, trading and storage decisions are directly influenced by the pricing and energy predictions [5], especially for BESS. When forecast accuracy is low (large mean absolute error), trading errors (the magnitude is as the square of the forecast error) increase and then diminish the expected profit for the storages technology that performs arbitrage in the spot market. Hence, the investment should go to the sophisticated hybrid models (AI/statistical) that prevails in minimizing prediction error, so as to ensure that the technical efficiency of intermittent renewable energy sources can be translated into enduring economic viability, which makes investment in storage practical and reliable.

Considered scenarios, its better economic performance with respect to the efficiency of the annual operating cost of reserves by producing simulated reductions of as much as 60% over traditional methodologies. Such simulated cost reduction can be explained by the fact that the dynamic model dynamically determines the reserve magnitude, and finds the lowest cost resources to offer ancillary services hour by hour, by super marginal and infra marginal thinking such that the resources nearest to the true marginal cost are used. In simulations, this also increases market efficiency and transparency as it reduces marginal cost displacement by 10–40%. The imperative for cutting ancillary service costs is keenly felt by grid operators, and knock-on benefits are positive for end users in the form of lower electricity bills.. Thus, under the modeled assumptions, the economic viability of renewable energy integration is tied to the ancillary services market's flexibility and its capability to efficiently compensate for instantaneous generation variability [4]

Table 7 shows that stochastic programming leads to a significant scale of cost increase when we move from an exogenous market model to an endogenous mathematical model with real time data on intermittent renewables, which supports hypothesis H4. The merit order policy is the baseline case and thus we extend the merit order block to the right to represent the total operating cost and the maximum potential displacement in terms of marginal cost, i.e. the block of the integrated dynamic algorithm should be beneath the merit order block. To that end, an integrated DP model illustrates, among the

Table 7: Economic Comparison of Reducing Ancillary Service Costs Between Traditional and Dynamic Models (Simulation-Based Results)

Reserve Determination Methodology	Average Reduction in Operating Costs (OC) per Year (%)	Reduction in Marginal Cost Displacement (MgC) (%)	Reserve Allocation Efficiency	Cost Comparison
Traditional Economic Merit List Methodology	0% (reference)	0% (reference)	Low (fixed allocation)	Very high
Technical Minimum Methodology	5	10	Medium	High
Integrated Dynamic Mathematical Model with Renewable Energy	Up to 60% (simulation estimate)	10% – 40%	High (flexible allocation)	Very low

Source: Simulation-based economic analysis of a flexible energy system (GAMS/CPLEX on modified IEEE 30-bus system). Statistical model: Standard time-based economic modeling to estimate opportunity cost. Software: GAMS with CPLEX solver, Python 3.10 for post-processing.

Table 8, by simulation, analyzes the value of forecasting intermittent renewable energy generation and the effect this has on trading decisions in the market, which is linked to BESS's financial benefits. The time-shifting ability to charge and discharge at the appropriate timing in the spot energy market is a key factor for making an ES system profitable.

Table 8: Analysis of the Relationship Between the Accuracy of Renewable Energy Forecasts and the Profitability of Energy Storage Systems in the Market (Simulation-Based Results)

Forecast Accuracy Measure (MAPE)	Expected Return on Investment for the Energy Storage System (%)	Average Trading Error (Megawatt Hours)	Average Storage Capacity Utilization (DoD)
High Accuracy (MAPE < 5%)	18	1.2 MWh	85%
Medium Accuracy (MAPE 5%–10%)	12	3.5 MWh	70%
Low Accuracy (MAPE > 10%)	5	7.8 MWh	45%
No Forecast	–2	15.0 MWh	30%

Source: Simulation-based analysis of operational and market data for a storage plant using synthetic data. Statistical model: Multiple linear regression model for sensitivity analysis of returns. Software: Python 3.10 with scikit-learn, pandas, and energy market simulation tools.

The rate of return is decreased significantly from 18 % (very high accuracy, MAPE < 5%) to 5 % (very low accuracy, MAPE > 10%). This sharp drop corroborates the modeled result that the presence of storage technology is not sufficient, without information and analysis infrastructure – such as advanced forecasting models (including LSTM as presented in Table 2) – storage technology can act as a financial burden. As decaying forecast accuracy increases the trading error on average from 1.2 MWh to 7.8 MWh, the energy storage device is persuaded not to choose an optimal timing to charge and discharge, thereby forfeiting arbitrage opportunities and causing the opportunity cost to increase. In the extreme ("No Forecast") case, the return turns negative (–2%), implying that investing in an energy storage device would be a financial gamble without a smart forecasting scheme. Accuracy of forecast can have an influence on the efficient utilization of the assets: storage capacity is used at an average depth of (DoD) of 85%, while with low accuracy, this average drops to 45%. This indicates that storage operates at low operational efficiency under uncertainty, reducing battery life and diminishing its ability to effectively provide ancillary services. The main conclusion is that digital transformation and advanced statistical modeling are prerequisites for the economic viability of energy storage technology [6].

4. Results

1. The VAR model analysis reveals a statistically significant positive relationship ($p < 0.001$) between wind energy penetration rate and grid frequency deviation. Specifically, a 1% increase in penetration causes a 0.72% increase in frequency variation. This demonstrates the direct effect of renewable intermittency on grid stability and highlights the necessity for fast control response and inertia compensation [Table 1].
2. Comparative results indicate that reactive power control (voltage and VAR control) using a smart transformer increases distribution line hosting capacity by up to 23% with only 1 MVA transformer capacity (operating at 96% of its rated reactive power limit). This is the most capital-efficient option compared to active storage [Table 3].
3. BESS, to provide a similar technical result (23% hosting capacity increase), requires substantially larger capital investment: 3.73 MW of inverter power capacity and 15.3 MWh of energy storage capacity, making it a considerably more costly solution [Table 3].
4. For advanced forecasting models, the LSTM model for peak load demand prediction achieved the best performance, with a MAPE of 3.1% and an R^2 of 0.97, compared to 6.8% and 0.88 for traditional MLR. This underscores the importance of AI in handling forecasting uncertainty [Table 2].
5. Dynamic mathematical modeling for ancillary services markets shows the potential to reduce annual reserve operating costs by up to 60% and decrease marginal cost displacement by 10% to 40% compared to traditional

economic merit order methods, significantly enhancing the economic viability of renewable energy integration [Table 7].

6. Increasing photovoltaic (PV) penetration degrades power quality. Average current total harmonic distortion (THD) rises to 5.9% at 50% penetration, exceeding the IEEE 519 current THD limit of 8.0% in 4.5% of measurements. Voltage THD remains acceptable (2.6%), indicating effective filtering but highlighting concerns for current-related apparatus and interharmonics [Table 5].
7. The economic profitability of BESS is critically dependent on forecast accuracy. The expected return on investment (ROI) drops sharply from 18% to 5% as the MAPE deteriorates from below 5% to above 10%. This underscores that technology alone is insufficient without advanced analytical infrastructure [Table 8].

5. Conclusions and Recommendations

1. Strengthen Regulatory and Technical Frameworks

- Regulatory bodies should mandate the adoption of advanced performance standards, specifically IEEE 1547-2018 Category III requirements for "disturbance ride-through," for distributed energy resources in high-penetration areas to ensure grid support during faults.
- Power quality standards (e.g., IEEE 519) should be updated to address emerging challenges such as interharmonics and supraharmonics from power electronics. Comprehensive metrics like Total Rated Current Distortion (as defined in IEEE 1547-2018) should be adopted for accurate assessment.

2. Invest in Digital and AI-Enabled Infrastructure

- Strategic investments should be directed toward developing and deploying hybrid (AI/statistical) forecasting models to achieve high-precision forecasts (MAPE < 4%). This is essential for maximizing BESS profitability, optimizing reserve allocation, and reducing ancillary service costs.

3. Reform Ancillary Services Markets

- System operators must transition to dynamic, real-time pricing models for ancillary services that integrate live data on intermittent renewable generation. This enables efficient, least-cost reserve procurement and avoids uneconomic dispatch of conventional units.

4. Support R&D for Cost-Effective Solutions

- Research funding should focus on optimizing smart transformer designs for operation at high reactive power limits and developing capital-efficient physical designs for renewable projects that minimize reliance on expensive, large-scale BESS.

5. Develop a Supportive Economic Policy Framework

- Market policies and mechanisms should be created to properly value and incentivize investment in grid-supportive technologies such as smart transformers and BESS, recognizing their critical role in providing ancillary services and ensuring system reliability during the energy transition.

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