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Modelling of Hybrid Solar - Wind system using different Switching Converters and Wind Turbines for Telecommunication Base Stations

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Abstract: In recent times continues power is required at remote telecom Base stations. This study built a hybrid solar–wind system (HSWS) using a type-4 wind turbine and a photovoltaic (PV) array, aiming to deliver steady, grid-ready power for BS even when the sun or wind don't cooperate. The real goal was to design and test behavioural modelling of HSWS in MATLAB/Simulink, where both wind and solar sources feed into a shared DC bus through their own DC–DC converters, then connect to the grid with an inverter. The investigation dive into how different DC–DC converter switches as MOSFET, GTO-diode, and IGBT with snubber diodes. As another case the impact of increasing the number of wind turbines, and the PVs short-circuit current (I_{sc}) shape the DC-link's behavior and the system's steady-state performance are investigated. Each energy source got its own DC–DC converter with smart switching controls for voltage regulation and maximum power point tracking (MPPT). Model has set the controller and hardware parameters like DC-bus regulator gains ($K_p = 1.1, K_i = 27.5$), a grid-side reactive power regulator gain (K_i = 0.05), a three-arm bridge inverter, and a snubber resistance (R_s = 1×10^5 Ω). To simulate real-world conditions, they used a 100 km, 50 Hz three-phase transmission line modeled with frequency-dependent RLC matrices at 100 kHz, which gave them balanced three-phase voltages (±60 kV), the proper 120° phase shift, and low distortion. DC-link voltage results offer exponential rise with some damped oscillations and ramped up fast but wobbled a bit due to switching and generator effects. The IGBT offers best configuration and had less voltage ripple. When they compared converter types the highest and steadiest DC-link voltage about 90-92 V for IGBT. The MOSFET and GTO switches offer 10% and 20% less DC voltages. Changing the PVs short-circuit current had a big effect on steady-state voltage levels to around 100 V at I_{sc}= 3.03 A, dropping to about 67 V at I_{sc}= 2.02 A. But there is no change in the time constants showing that the system's dynamic response stayed solid. In the end, this HSWS can reliably power telecommunication loads (about 1.5 kW, right in the 1–3 kW range). The IGBT-based setup gives the best mix of DC-link stability and efficiency, making it a strong choice for hybrid renewable energy systems.

Key Words: Hybrid Solar - Wind System, Telecom BS, Behavioural Modelling, DC-DC converter, MPPT, IGBT switching, PWM, Wind Turbines Impact.

1. Introduction

Telecom in India has exploded over the last decade, and with it, the need for steady, reliable power at every base station (BS). With millions of new mobile users and data services popping up everywhere, these networks can't afford downtime. Each telecom BS is equipped with transceivers, signal processors, cooling fans, and backup gear-guzzles electricity. Most sites need around 1 to 3 kW of nonstop power, though the exact number depends on how much equipment is running and how busy things get. The real challenge starts in rural or remote areas, where the grid is flaky or just doesn't reach. Out there, operators lean on diesel generators for backup. But running on diesel gets expensive fast, not to mention the hassle of hauling fuel across bad roads. Plus, it's dirty-diesel means more pollution and a bigger carbon footprint. Thus, this research is motivated to design and investigate the hybrid renewable energy model for such BS sites. the aim is to design Simulink model for behavioural testing of s=hybrid solar-

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wind energy model with different switching option for DC converter bridge. India's telecom network is one of the world's biggest, anchored by groups like TRAI and giants like Airtel, Reliance Jio, and Vodafone Idea. Here's the thing: A huge chunk of those towers sits in places where the grid is patchy at best. Power cuts and voltage swings are the norm, pushing operators to rely even more on diesel. the proposed hybrid model aims to serve the continuous power of these sites and may improve the network coverage.

More and more, people are looking to renewables to power these base stations. Solar and wind stand out—they're everywhere, and they actually work well together. Solar kicks in during the day, while wind can pick up the slack at night or when it's cloudy. Put both together in a hybrid solar-wind setup, and you get steadier, more reliable power than just going with one or the other. These hybrids slash diesel use, cut emissions, and make sure those towers keep humming along, even off the grid. Of course, making these hybrid systems work takes some smart engineering. It needs the right design, good modelling, and sharp power management. Power electronic switching converters are the real workhorses here—they juggle the energy between solar panels, wind turbines, batteries, and the telecom equipment. Whether it's DC-DC boost converters, buck converters, or bidirectional ones, picking the right converter and control system is key. Get it right, and you boost efficiency, nail voltage stability, and keep losses down.

That's why designing and modelling hybrid solar-wind systems with the best switching converters is such a hot research area for India's telecom sector. The goal is simple: build a system that's reliable, affordable, and green—especially for those tough, off-grid spots. By blending renewables with state-of-the-art power electronics, these hybrid systems can keep the signal strong, cut fossil fuel use, and help India build a cleaner, more sustainable telecom network. The Figure 1 have represented our proposed system architecture for Telecom BS's.

Figure.1 System Diagram of the Hybrid Solar-Wind Based Telecom Base Stations

Telecommunication BS's keep demanding more energy, and old-school grid power just isn't cutting it anymore. So, researchers have started turning to renewable energy solutions as in Figure 1. Pragya Nema et al [1] were among the first to show that combining solar panels and wind turbines can really make a difference for GSM/CDMA mobile base stations. Their approach boosted energy availability and cut down the need for diesel generators. Building on that, R. R. Sawant's et al [2] showed that rooftop mobile towers can run on PV-based hybrid

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power plants, which not only save money but also shrink the environmental footprint. G. Modi [3] took things a step further with solar PV battery setups designed just for telecom towers, and they managed to make the whole system more reliable by improving how energy gets stored and managed. Then Farzana Alam et al [4], who dug into how solar–wind hybrid setups actually perform. They found that mixing different renewables makes the whole system more stable and keeps the power flowing. On the technical side, Garimella Mohan et al [5] have used MATLAB/Simulink models to test how hybrid solar–wind systems hold up under different real-world conditions. Meanwhile, M. S. Khesbak and A. A. Ibraheem [4] focused on solar-powered systems for mobile base stations and pointed out just how important good power management and smart system design really are. All these studies add up to one thing: Hybrid renewable energy systems—especially those mixing solar and wind—really do offer a solid and sustainable way to power telecom infrastructure. Since solar and wind tend to work well together and cover for each other's weak spots, hybrid systems keep the power on, even in remote places where the grid just isn't reliable.

This research aimed to investigate the different switch operations for universal bridge converter used for designing the Solar-wind system. the ultimate aim is to improve the output power of the system. The wind system converter is used under this study and is modelled with three different switches along with 3 arm structure and (pulse width Modulation) PWM. Especially a study investigated the impact of increasing wind system parameters on voltage or power profile

2. Challenges of HSWS Design

There various design and implementation challenges faced during modelling and simulation of the HSWS system design. Figure 2 shows the main hurdles in modelling how HSWS systems behave.

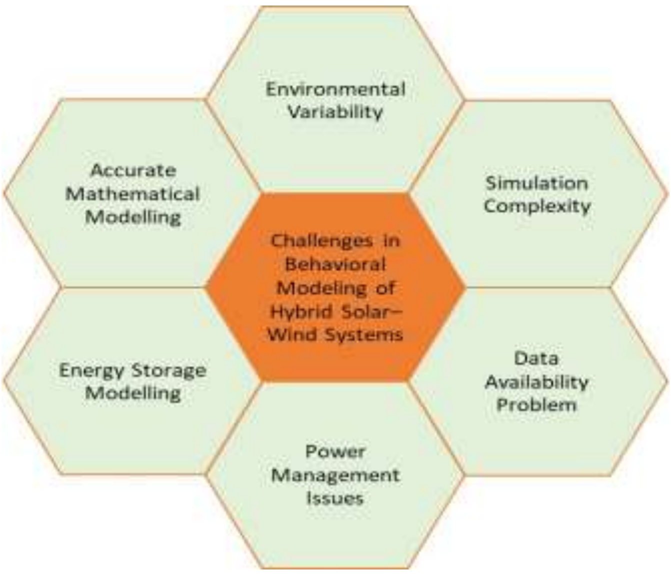

Figure.2 Challenges in Behavioral Modelling of Hybrid Solar-Wind Systems

First, there's the environment-it never sits still. Sunlight and wind speed are always changing, so it's tough to predict how the system will act from one moment to the next. Then comes the tricky part of math. You need models that really capture how solar panels, wind turbines, converters, and controllers behave, and their quirks aren't exactly simple or linear. Add to that the headache of simulation. When it starts combining together all the different blocks, generators, converters, and control systems the whole thing gets complicated fast. And don't expect to find a ton of good data to help you out. Reliable, long-term numbers about the

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environment and how these systems actually run are pretty rare. Let's not forget energy storage. Batteries and other storage systems have their own way of charging and discharging, and those details play a big role in keeping the system steady and working well. On top of all this, it has to juggle power management and making sure the energy from solar, wind, and storage gets to where it needs to go, when it's needed. All these challenges really drive home the need for smarter models and intelligent control methods if we want hybrid renewable energy systems to run smoothly and reliably.

3. Applications of the HSWS Modelling and Design

There are many applications to investigate the behavioural modelling of the hybrid solar-wind energy systems. Most relevant ones are illustrated in Figure 3.

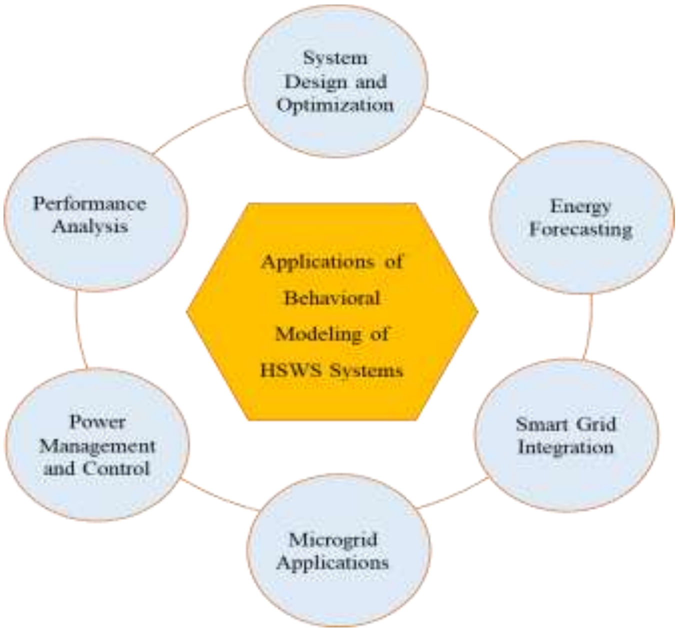

Figure.3 Applications of Behavioral Modelling of Hybrid Solar–Wind Systems

Figure 3 shows just how many ways we can use behavioural modelling in HSWS. The idea of studding uses of behavioural modelling, to make these systems smarter and more effective. There are six main areas where these insights really make a difference, from day-to-day operations to big-picture planning. First, there's system design and optimization. Here, behavioural modelling helps engineers play out different scenarios between solar and wind, so they can figure out the best sizes, setups, and costs for a project.

Then HSWS systems are used for energy forecasting. With these models, we get a better handle on how unpredictable renewable energy can be—so we can make much sharper predictions, both for tomorrow and for the long haul. That's huge for keeping everything running smoothly. Smart grid integration comes next. The models help HSWS work well with smart grids, keeping things stable, matching energy supply to demand, and making sure energy moves efficiently where it's needed.

Microgrid applications also benefit. By understanding behaviour in detail, we can make microgrids tougher and more flexible, balancing local generation, battery storage, and shifting demands-even when conditions change. In power management and control, advanced models let us adjust on the fly. They help balance what's being generated with what's being used, cut down on waste, and squeeze out every bit of efficiency. Finally, performance analysis ties it all

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together. By constantly tracking how the system behaves, we spot problems early, keep things running at their best, and keep improving over time. All these pieces show just how important behavioural modelling is for HSWS. It connects the technical side of things with real-world performance, helping bring smart, reliable renewable energy to the grid.

4. Literature Review

Several studies have explored the use of hybrid renewable energy systems to improve the reliability and efficiency of telecom power supplies. Pragya Nema et al. [1] proposed a hybrid solar–wind system for GSM/CDMA base stations using HOMER software to determine the optimal configuration of PV panels, wind turbines, and diesel backup. Similarly, Sawant et al. [2] developed a hybrid telecom power plant integrating rooftop solar with grid power using MPPT-based rectifier systems for improved energy utilization. Modi et al. [3] designed a solar PV battery backup system capable of operating in both grid-connected and standalone modes while maintaining voltage stability and power quality. Studies by Farzana Alam et al. [4] and Garimella Mohan Krishna Sairam et al. [5] demonstrated that solar–wind hybrid systems can effectively generate clean energy and reduce reliance on conventional sources.

Research has also focused on renewable energy system design and optimization. Khesbak et al. [6] proposed a solar-powered system for telecom base stations with efficient DC–DC power conversion. Hongxing Yang et al. [7] introduced an optimization model for PV–wind hybrid systems with battery storage based on cost minimization and loss of power supply probability. Additional studies explored hybrid system modelling, power electronics integration, and system efficiency improvements using converters, inverters, and advanced control techniques [9–13].

Other works have examined renewable energy adoption, hybrid system applications, and microgrid development. Alipour et al. [14] investigated factors influencing solar PV and battery adoption, while Amoussou et al. [15] evaluated hybrid renewable energy systems for reliable residential power supply. Hybrid systems combining solar, wind, fuel cells, and energy storage have also been explored for improved reliability and energy management [16–18]. Furthermore, several studies analyzed control strategies, smart grids, and renewable integration for sustainable energy systems. Research on hybrid converters, smart grid modelling, and renewable energy-powered buildings highlights the growing importance of integrated renewable solutions [19–22]. Hybrid renewable systems have also been proposed for telecom stations, rural electrification, and microgrid applications, demonstrating their potential to provide reliable and cost-effective power supply [23–27].

Table.1 Summary of Literature Review and Limitations

Reference	Methodology	Outcomes	Limitations
Pragya Nema et al. [1]	Hybrid solar–wind–diesel system modeled using HOMER with real climatic data	Optimal configuration for powering telecom base stations efficiently	Limited to specific geographic data (Bhopal); lacks real-time implementation
Sawant et al. [2]	Hybrid telecom power plant integrating rooftop solar with grid using MPPT-based rectifiers	Improved power reliability and efficient solar integration	Dependent on grid availability; limited renewable penetration

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Modi et al. [3]	Solar PV battery system with adaptive and resonant control for telecom loads	Maintains voltage stability and supports both grid and standalone operation	Performance depends on battery capacity and solar availability
Alam et al. [4]	Solar–wind hybrid generation with battery storage and charge controller	Demonstrates renewable energy integration for small-scale loads	Prototype-level study with limited scalability
Sairam et al. [5]	Hybrid wind–solar system using DC/DC boost converter and inverter	Clean energy generation and reduced dependence on fossil fuels	Lack of optimization strategy and system control analysis
Khesbak et al. [6]	Solar-powered system with optimized PV array and DC–DC converter	Ensures uninterrupted telecom operation during grid failure	Sole reliance on solar energy reduces reliability in low irradiance
Yang et al. [7]	Optimization model for PV–wind hybrid system with battery storage based on LPSP	Reduced system cost while maintaining supply reliability	Requires accurate climatic data and system sizing
Prashanth et al. [8]	Conceptual discussion of renewable energy benefits	Highlights environmental advantages of renewable energy	Not technically focused; lacks experimental validation
Khokhar et al. [9]	MATLAB/SIMULINK modelling of power quality disturbances	Demonstrates effects of voltage sag, swell, and harmonics	Focused only on disturbance analysis, not renewable integration
Shagar et al. [10]	Front-end converter design for hybrid wind–solar system	Improved energy extraction and power quality	Limited experimental validation
Hole et al. [11]	Review of PV inverter technologies	Identifies inverter role in improving PV system efficiency	Primarily review-based; lacks system-level evaluation
Lamnatou et al. [12]	Modelling analysis of building-integrated solar systems	Provides classification of PV/PVT modelling approaches	Focus limited to building applications
Cvetkovic et al. [13]	Two-port network modelling for nonlinear power converters	Enables black-box modelling of renewable converters	Complex modelling approach with limited practical validation
Alipour et al. [14]	Survey and modelling of PV and battery adoption behavior	Identifies socioeconomic factors influencing renewable adoption	Region-specific study
Amoussou et al. [15]	Optimization of hybrid renewable systems using COE and LPSP metrics	Identifies reliable and cost-effective power configurations	Focused on residential systems
Nema et al. [16]	Review of hybrid renewable energy systems	Highlights advantages of combining wind and solar energy	Conceptual discussion without implementation
Uzunoglu et al. [17]	Hybrid PV–fuel cell–ultracapacitor energy system	Ensures reliable energy supply through multi-source integration	Complex system design and high cost
Jenkins et al. [18]	HOMER-based feasibility analysis of wind–solar hybrid systems	Identifies optimal renewable energy generation sites	Site-specific analysis
Lawan et al. [19]	Review of wind–PV hybrid system technologies	Discusses challenges and integration strategies	Limited quantitative analysis
Yamini et al. [20]	Model Predictive Control for hybrid PV–battery MMC system	Improved voltage balancing and grid stability	High computational complexity
Mekkaoui et al. [21]	Smart grid modelling using MATLAB/SIMULINK	Analyzed active power flow and system stability	Focused on simulation rather than implementation
Icaza et al. [22]	Hybrid solar–wind system for sustainable building energy	Demonstrates renewable integration in organic architecture	Limited scalability and practical deployment
Bhattacharya et al. [23]	Hybrid renewable system for rural telecom stations	Provides reliable power supply for remote areas	Limited energy storage analysis
Huang et al. [24]	Multi-turbine wind–solar hybrid system using TRNSYS simulation	Improved performance at low wind speeds	Increased system complexity
Abdulridha et al. [25]	Simulation modelling of hybrid renewable systems for DC loads	Demonstrates energy flow management in hybrid systems	Simulation-based without real-world validation
Ullah et al. [26]	HOMER Pro-based hybrid microgrid design with battery storage	Optimized renewable utilization for rural electrification	Dependent on accurate weather data
Olaogun et al. [27]	Hybrid solar–wind system with diesel backup for telecom networks	Reliable and cost-effective energy supply in remote areas	Continued reliance on diesel backup

The reviewed studies primarily focus on hybrid renewable energy systems for telecom and microgrid applications; however, most works rely mainly on simulation-based analysis with limited real-time implementation and experimental validation. it is required to investigate the behavioural analysis under different parametric impacts. Additionally, existing approaches often lack advanced control strategies and optimization techniques for efficient power management, highlighting the need for improved hybrid system designs with enhanced reliability, scalability, and intelligent energy management. This research has presented three case studies on validated Simulink model for HSWS design

5. Proposed Modelling of HSWS

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This hybrid renewable energy system (HSWS) pulls together wind and solar power using a smart control strategy. It works with a Type-4 wind turbine and a solar (PV) array each feed their electricity into their own DC–DC converters. These converters smooth out the naturally fluctuating energy from the wind and sun, keeping the voltage steady on a shared DC bus. From there, an inverter bridge steps in, turning that stable DC power into AC that can go straight to the grid or power local loads. This setup is modular, so it's flexible, reliable, and can quickly respond when the weather changes. Thus, in this proposed work it is to design and model the HSWS Simulink model with three different switches as MOSFET, GTP and IGBT with snubber diodes. The first part of research modelled DC -DC converter with these switching operations

The Figure 4 lays out the basic block diagram for this hybrid solar–wind system. Both the wind turbine and the solar panels send their output through their own DC–DC converters, which handle voltage regulation and keep the system locked on to the maximum power point (MPPT). All this feeds into the same DC bus, which then connects to an inverter. The inverter flips the DC into AC, making it easy to tie into grid infrastructure or run standalone loads. The diagram really highlights just how streamlined and modular the whole setup is.

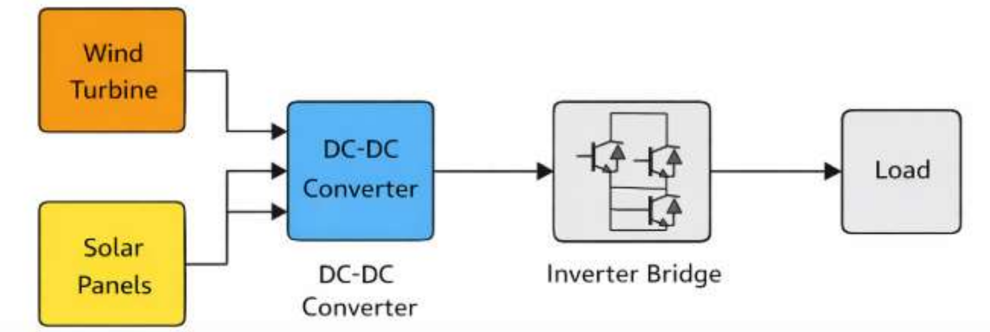

Figure.4 Basic Block Diagram of the HSWS Design

The real magic happens with the converter switching mechanism. This part controls how long the power electronic switches stay on inside each DC–DC converter, constantly tweaking voltage and current output. On the solar side, it reacts to changes in sunlight and temperature to keep MPPT running smoothly. On the wind side, it keeps up with shifts in turbine speed and torque. By coordinating switching between both converters, the system squeezes out as much energy as possible, keeps voltage stable, and balances the load in real time. This switching mechanism isn't just a feature-it's at the heart of making the whole hybrid system work efficiently. The proposed MATLAB Simulink model as validated and designed is illustrated in the Figure 5. The blocks as highlighted by the rectangular boxes are modified for the result investigations.

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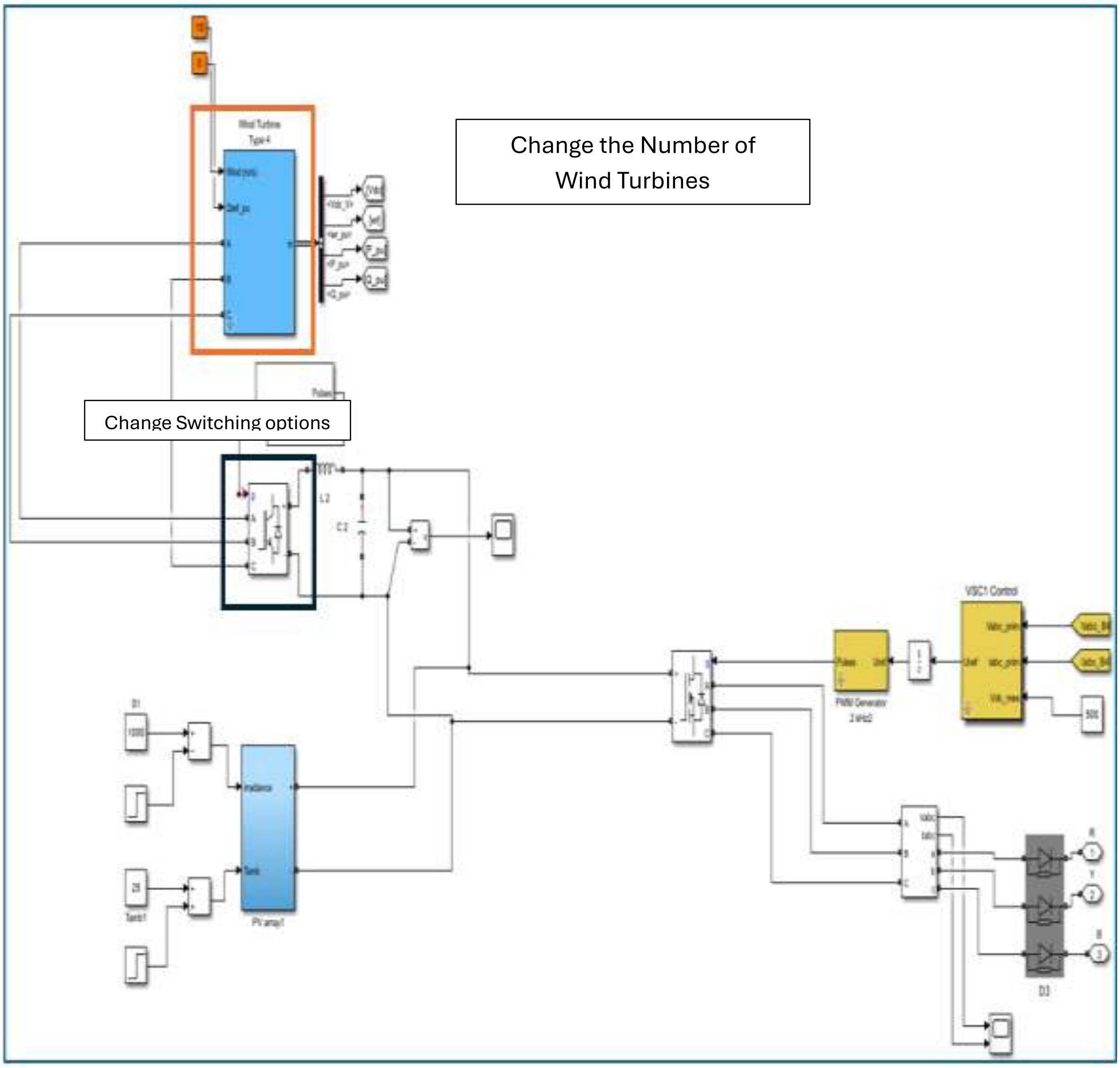

Figure.4 Proposed Subsystem for Simulink Model for the HSWS Design

The DC voltage in the wind power system jumps up in a way that looks like a first-order exponential curve, but there's also a bit of a wobble—those are the ripples you see right when the system starts up.

1. General DC Voltage Model: the basic mathematical model for this DC voltage response is:

$$V(t) = V_{ss}(1 - e^{-kt}) + Ae^{-bt}\sin(\omega t) \quad (1)$$

where;

$V(t)$ = DC output voltage at time t

V_{ss} = steady-state DC voltage

k = system rise constant, A = oscillation amplitude

b = damping coefficient,

ω = oscillation frequency and t = time

The first part of the equation shows how the voltage slowly climbs toward its steady value. The second part captures those quick, shaky oscillations that happen because of things like switching converters and the generator's own quirks.

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2. Case (a): $NT = 1$: For the first configuration the voltage response is

$$V_1(t) = 90(1 - e^{-7t}) + 3e^{-6t}\sin(120t) \quad (2)$$

It is the best-case scenario, the system reaches its steady voltage faster and with fewer ripples-so you get a sharper, more stable response.

3. Case (b): $NT = 2$: For the second configuration

$$V_2(t) = 90(1 - e^{-4.5t}) + 4e^{-4t}\sin(120t) \quad (3)$$

The system shows moderate rise speed and oscillation amplitude.

4. Case (c): $NT = 3$: For the third configuration

$$V_3(t) = 90(1 - e^{-3t}) + 5e^{-3t}\sin(120t) \quad (4)$$

This case exhibits the slowest rise response and highest oscillatory behaviour, indicating reduced damping in the system.

5. Comparative Model: The three responses can be summarized in a unified form:

$$V_{NT}(t) = V_{ss}(1 - e^{-k_{NT}t}) + A_{NT}e^{-b_{NT}t}\sin(\omega t) \quad (5)$$

where the parameters k_{NT}, A_{NT}, and b_{NT}vary depending on the number of turbines NT. But if added more turbines (NT), the system takes a little longer to settle. The voltage rise slows down and the ripples get bigger, so it’s less dynamic and you end up with more noticeable bumps in the DC voltage.

6. Results and Discussions

This section presented the experimental outcomes and discussion for the various parametric studies carried out as a part of this research.

6.1 Waveform and DC Voltage Validation

This section presented the validation results for the existing HSWS design model. The model parameters are defined and the output waveforms and response are validated.

Line parameter Calculation: The transmission line parameters presented correspond to a 100 km power transmission line operating at 50 Hz, where the frequency-dependent line parameters are stored in the WB structure of the simulation model. The RLC matrices calculated at 100 kHz describe the electrical characteristics of the three-phase line, including the resistance (R), inductance (L), and capacitance (C) per KM. The resistance matrix indicates the conductor resistance and the mutual coupling between phases, while the inductance matrix represents both self and mutual inductances caused by the magnetic field interactions among the conductors. Similarly, the capacitance matrix shows the electrostatic coupling between phases and ground. Additionally, the positive- and zero-sequence parameters provide simplified representations of the transmission line for symmetrical component analysis. The positive-sequence values represent the balanced operating condition of the system, whereas the zero-sequence parameters describe the line behaviour during unbalanced conditions such as ground faults. These parameters are essential for accurately modelling the dynamic performance and electromagnetic characteristics of the transmission line in power system simulations.

The parameters used for the design and modelling the hybrid HSWS system model in Simulink are illustrated in the Table 2. the parameter in bold are varied for the investigation of performance under study. Table describes the parameters for three different blocks of the model as Wind system, Solar PV array, and DC-DC converter Block as universal bridge.

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Table.2 Design Parameters Table

Block	Parameter and Values	Significance
Wind System	**Number of wind turbines: NT= 1, 3 or 5**	Defines the system scale; here, a single turbine is modelled.
	DC bus voltage regulator gains [Kp, Ki]: [1.1, 27.5]	Maintains stable DC bus voltage by adjusting converter output; critical for system stability.
	Grid-side converter var regulator gain [Ki]: 0.05	Controls reactive power exchange with the grid, supporting voltage regulation.
DC-DC Converter Bridge	Number of bridge arms: 3	Defines the topology of the converter; three arms correspond to a three-phase bridge structure.
	Snubber resistance Rs (Ω): 1e5	Provides damping for transient voltages across switching devices, improving stability and reducing oscillations.
	Power Electronic device: MOSFET, GTO or IGBT / Diodes	Specifies the semiconductor devices used; IGBTs handle switching, while diodes provide freewheeling paths.
Solar PV array system	Solar irradiance 1000	Intensity of sun light kept maximum signifies the maximum performance of PV system
	Temperate $25^o\ C$	Normal average temperate of environment at PV panels
	I_{sc} = 2.02 A	Short circuit current rating. of PV cells

6.2 Validation of HSWS Model

The model is validated for HSWS system by simulating to test how it would perform during power transmission. The waveforms are validated in the Figure 5, it shows the output voltages for all three phases. The waveforms look just good enough to be used for AC mains: smooth, sinusoidal, and balanced in both amplitude and phase. That’s a good sign. It means the HSWS design really does a solid job at producing stable transmission voltages. The yellow, magenta, and cyan lines each stand for one phase of the transmission. They’re all perfectly in sync, with a steady 120° phase shift between them, which keeps the system properly synchronized.

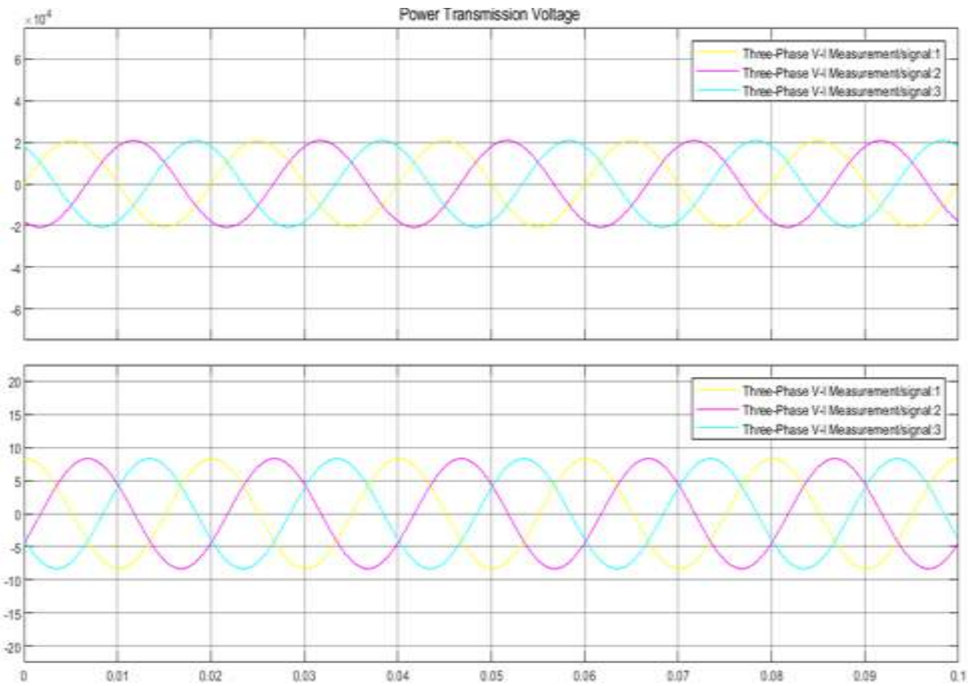

Figure.5 Output 3-Phase Waveform for Proposed HSWS at Power Transmission

Now, check out the top plot in Figure 5. It shows the voltage at transmission level, swinging between -60,000 and +60,000. That’s exactly what you want to see in a high-voltage

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system and have no sign of distortion, just clean, reliable power. So, the HSWS holds up under real transmission conditions. Down in the bottom plot are scaled down and normalized waveforms between -20 and +20. Even after normalization, the signal shapes stay intact. That means the system keeps everything proportional and balanced across all three phases. Finally, look at the all signals in Figure 5. They're steady and repeat without any weird harmonics or imbalances. That tells you the HSWS model is stable and robust. All in all, these results show the HSWS can reliably generate the kind of three-phase transmission voltages you need for big power delivery systems.

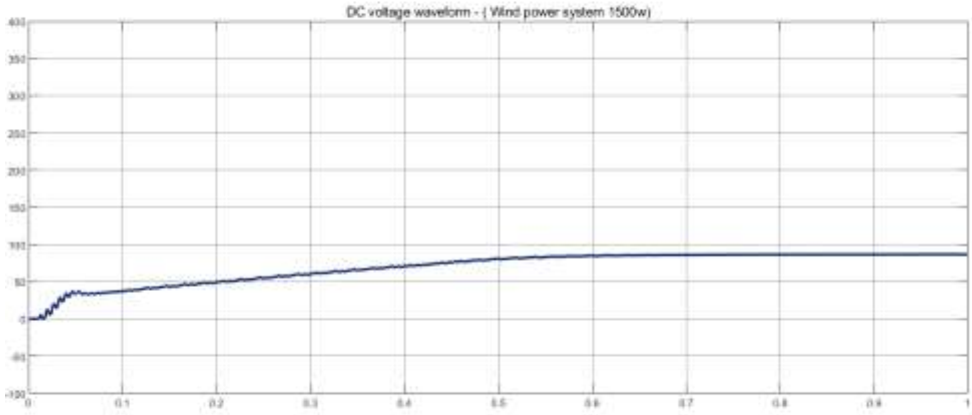

Figure.6 Validation of Power Curve for IGBT Converter in Solar Wind System

The validated DC voltage output for wind system NT=1, with IGBT switching as DC-DC converter are shown in the Figure 6. Wind system is validated for 1500 W (1.5 KW) power. It can be observed from the Figure 6 that the designed model is best suited for the average daily uses of the Telecom BS of 1.5 KW of power (raging 1-3 KW).

6.3 Impact of DC-DC converter Switches

An experiment is performed by varying the different switches for DC-DC converter design. it is to determine which switching suits best for the Telecom operations.

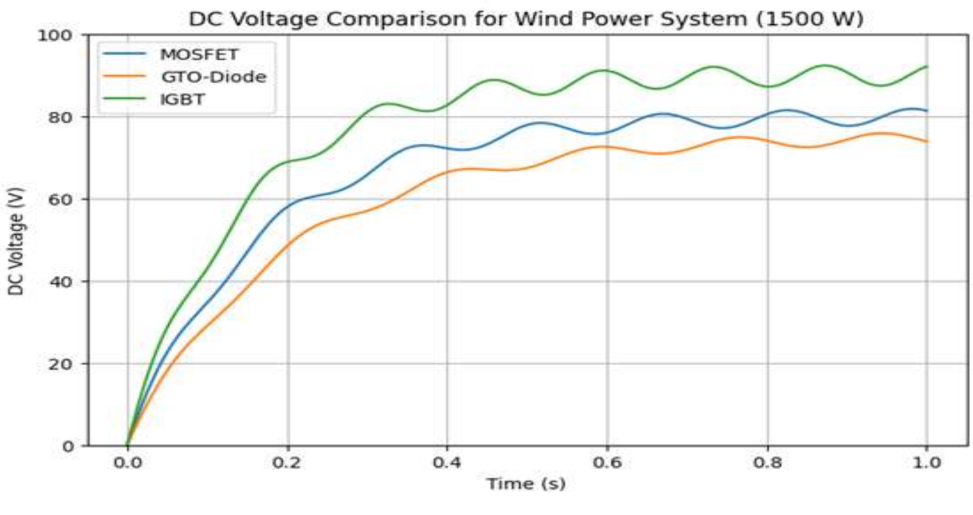

Figure.7 Results Presented the Case Investigation of Wind System with Three Different Switching Option for DC Converter Bridge

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Figure 7 shows how the wind energy conversion of HSWS system, performs with three different switching devices in the DC converter bridge: MOSFET, GTO-Diode, and IGBT. The graph tracks DC-link voltage over time for each one. At first, the DC voltage shoots up from zero, then settles into a steady level as things stabilize. When you look at the numbers, the IGBT-based converter stands out. Its steady-state DC voltage hits about 90 to 92 volts, which means it keeps voltage stable and transfers power efficiently.

The MOSFET setup lands a bit lower at around 80 to 82 volts, but it reacts faster thanks to its quick switching. On the other hand, the GTO-Diode converter comes in last, with a steady voltage around 73 to 75 volts and a slower response during the transient phase. Put simply, the IGBT delivers the best voltage stability and highest DC-link voltage. The MOSFET isn't far behind—it's faster, just not as strong on voltage. The GTO-Diode trails both in voltage and response time, so it's not the best pick if you want a high-efficiency wind energy conversion system.

6.4 Impact of Number of Wind Turbines

As a second study in research the impact of varying the number of wind turbines (NT) increment on the DC voltage profile and system behaviour. Figure 8 compares how the wind power system's DC voltage (at 1500 W) reacts over the first second when you set number of turbines (NT) to 1, 3, or 5. The results basically shows how quickly the system reacts, how fast the voltage rises, and how it settles down, depending on how you tune NT.

It is clear from Figure 8 that right after start up, between 0 and 0.1 seconds, the DC voltage shoots up fast in all three cases. But the NT = 1 setup (that's the red line) jumps up the quickest. It hits a higher voltage in less time than the other two. By about 0.4 or 0.5 seconds, it's already near steady-state, which tells you this setting is really good at grabbing energy and regulating fast.

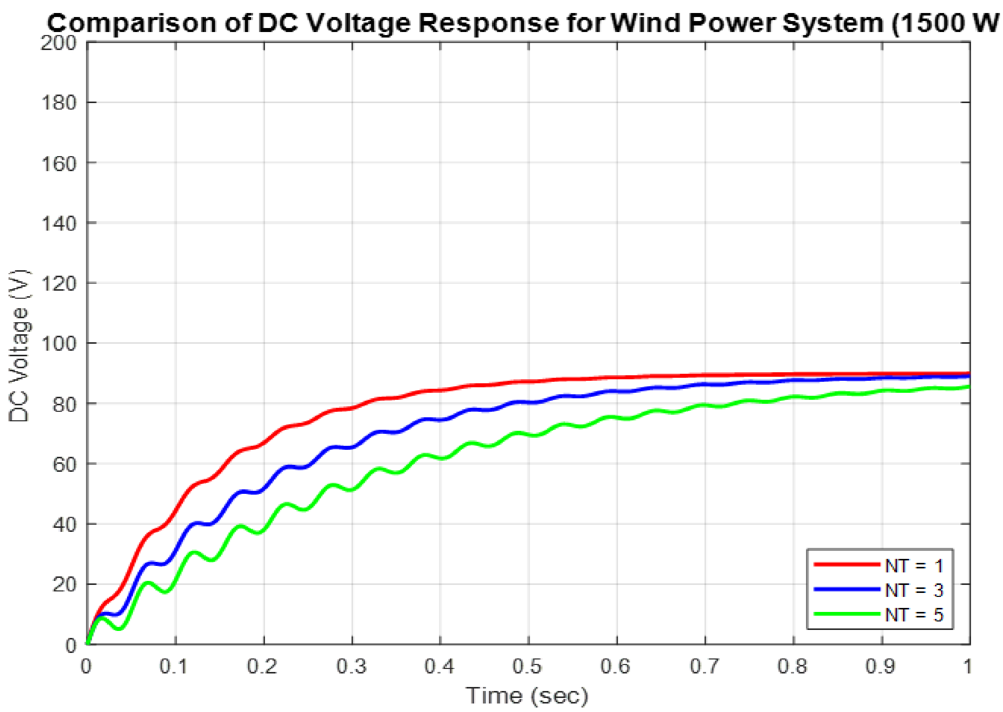

Figure.8 Results and Impact of Increasing Wind Turbines

With NT = 3 (the blue line in Figure 8), the voltage still climbs steadily, but it takes a little longer to settle. The rise is smoother, and you see fewer swings in the curve, so the system

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feels more stable and controlled. NT = 5 (the green line) is even slower. The voltage creeps up more gradually, and it takes its time getting close to steady-state. That means the system's playing it safe — energy transfer at the start isn't as aggressive, but you get better damping and smoother transitions. To summarize when it cranks up NT, the system slows down but smooths out, this trade speed for stability and less aggressive behaviour. Lower NT settings let the voltage build up faster and stabilize quickly. Good for grabbing power fast, but you might see a bit more bounce in the response. All in all, NT = 1 gives you the speediest reaction and the highest steady-state voltage. NT = 5 trades speed for a smoother, slower approach. NT = 3 is the middle ground, fast enough, but still steady and which makes it a solid choice for wind energy systems where you want both speed and stability.

6.5 Impact of I_{sc} of PV system

The impact on wind energy conversion system's DC voltage is analysed under two short-circuit current (I_{sc}) conditions: 3.03 A and 2.02 A. The aerodynamic power equation governs the electrical power generated by wind turbines.

$$P_{wind} = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{6}$$

The extracted wind power is dependent upon air density, rotors swept area, wind speed, as well as turbine power coefficient. The generator converts mechanical power into electrical power with an efficiency of η_g. The DC output voltage is directly linked to the power source and current as follows:

$$V_{dc}(t) = \frac{P_{elec}(t)}{I_{dc}(t)} \tag{7}$$

Figure 9 displays the experimental results, which show that the DC voltage waveform undergoes a transient exponential climb before reaching steady state.

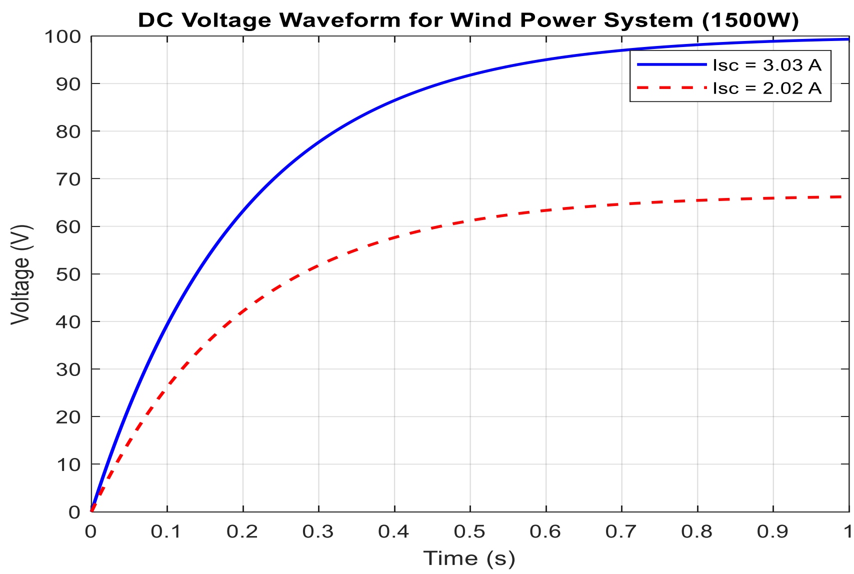

Figure.9 Impact of Varying the I_{sc} on Dc Voltage Output

Which can be modelled as

$$V_{dc}(t) = V_{ss}(1 - e^{-\alpha t}), \tag{8}$$

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where, V_{ss} stands for the steady-state voltage, and α is the response constant, shaped by the generator's inertia and the converter's dynamics. When I_{sc} is 3.03 A, the voltage settles at about 100 V. Dropping I_{sc} to 2.02 A, and the steady-state voltage falls to roughly 67 V. In both cases, the systems react in pretty much the same way and the time constants match up, so changing the short-circuit current doesn't really mess with how the system responds over time.

What really changes are the steady-state voltage itself. The transient response is the way the system settles down after a disturbance—stays tied to the core electromechanical dynamics of the wind generator and the power electronics. So, the results show that the hybrid solar–wind setup keeps a steady voltage, even as the I_{sc} current shifts. It's a solid sign that the system handles different loads well and doesn't lose its stability.

7. Conclusions and Future Scopes

The prosed research has designed HSWS system brings together wind and solar power in a pretty smart way for Telecom BS. It uses a modular setup with DC–DC converters that run on different switching devices. The simulations show the system delivers a steady, balanced three-phase AC output. That means it works well whether you're hooking it up to the grid or just powering local loads.

It is concluded that amongst the different switching technologies, the IGBT-based converter clearly stands out with DC voltage ranging 90-92 V. It keeps the DC-link voltage nearly 10% and 20 more stable and boosts efficiency better than MOSFETs or GTOs respectively. That's mostly because it cuts down on voltage ripple and has better switching performance. as another study it is noted that adding more wind turbines, the system's stability and damping get even better, though there's a small trade-off the voltage takes a bit longer to rise. So, you get a sturdier system, but the dynamic response slows down just a little. Testing the system with different I_{sc} current levels show that, while the steady-state voltage shifts, the way the system handles sudden changes hardly budges. In other words, the HSWS keeps its cool and stays reliable, even when the load or conditions change. This setup can easily handle telecom base station loads in the 1–3 kW range. That makes it a strong candidate for remote or off-grid sites. The modular design means you can scale it up or add more renewable sources if you need to.

Looking ahead, in future there's room to make things even better. Tweaking the converter's switching controls could sharpen the system's response and cut down on power losses. Smarter, more adaptive maximum power point tracking (MPPT) algorithms could help squeeze out more efficiency, especially when the weather's all over the place. And if you add energy storage and batteries or supercapacitors it will get even steadier power, even when the sun or wind isn't cooperating. There's also a lot to gain by digging deeper into how the system interacts with the grid and handles faults, especially as the model gets expanded.

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