

EFFICIENT RESIDENTIAL EV CHARGING USING PHOTOVOLTAIC ENERGY AND INTELLIGENT ENERGY SCHEDULING

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ABSTRACT:

As EVs become increasingly popular, the need for charging infrastructure has surged, especially for its efficiency, cost-effectiveness, and eco-friendliness. The project, Adaptive Solar-Assisted Residential EV Charging System with Intelligent Energy Management and Vehicle-to-Home Support, focuses on maximizing energy use and minimizing reliance on traditional electric distribution systems. The designed system includes a PV generation system, home loads, EV batteries, bidirectional power converters, and an adaptive control system to ensure energy management reliability and economic viability. Household loads, EVs are powered by solar energy and this reduces electricity costs and carbon emissions. A pricing-based control strategy is implemented to control the electricity tariff, the battery state of charge, and availability of renewable energy, for smart charging and discharging. When tariffs are low, the electricity generated by both solar panel and network sources is used to charge the battery, while when tariffs are high, the stored battery energy can be used to supply residential loads using the Vehicle-to-Home (V2H) function. In addition, the system has a least Incosh based control algorithm for operation of the Voltage Source Converter (VSC), which provide harmonic suppression, near-unity power factor operation, reactive power compensation and voltage regulation. MATLAB/Simulink simulations are used to test the proposed framework in a range of solar irradiance conditions, under different electricity pricing conditions, and under different load conditions. Results show that grid energy use is significantly reduced, costs of charging are reduced and peak demand is reduced, with no reduction in operation and no degradation in power quality. The proposed system is a practical and sustainable approach for future smart residential energy networks, enabling the integration of renewable energy resources, intelligent energy scheduling, and bidirectional energy flow from EVs, which will improve energy efficiency, economic advantages, and environmental sustainability.

Keywords: Electric Vehicles (EVs), Solar Photovoltaic System (PVS), Residential Charging Infrastructure (RCI), Vehicle-to-Home (V2H), Adaptive Energy Management (AEM), Dynamic Pricing, Renewable Energy Integration, Smart Grid, Bidirectional Charging, Power Quality Improvement, Voltage Source Converter (VSC), and Intelligent Control System.

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I. INTRODUCTION

Electric vehicles (EVs) have revolutionized the transportation industry with their swift expansion and their offer of an alternative to traditional fossil-fuel powered vehicles that is

both cleaner and more sustainable. Due to the rising concerns about environmental pollution, greenhouse gas emissions and the lack of non-renewable resources, the governments and industries have begun to encourage EV usage

by implementing supportive policy and development of EV infrastructure [1]. The introduction of EVs has, however, come with a number of problems such as the deployment of charging stations, grid congestion, charging costs and power quality issues. Convenience and availability put residential charging as one of the most preferred charging methods. However, when charging occurs during a period of peak demand, uncontrolled charging could place a strain on the electricity distribution network and cause price increases for electricity consumers. The challenges have led to the integration of renewable energy resources with residential EV charging infrastructure as a potential solution. However, solar photovoltaic (PV) systems have some major benefits compared with other renewable energy technologies as they are clean, readily available, and have a low operating cost for producing energy. Solar-assisted EV charging can provide the opportunity to use sunlight as a renewable resource for powering EVs, rather than relying on the electricity grid, which can help to lower carbon emissions. The sun is however a variable source of energy, which demands a smart energy management approach which can coordinate the exchange of energy between solar generation systems, domestic loads, grid and electric vehicle batteries for reliable and efficient operation [2].

Advancements in smart grid technologies have paved the way for smart residential energy management solutions that can optimize energy usage and enhance energy system efficiency. The energy landscape is becoming prosumerized: consumers are not only using electricity but also producing and storing energy from decentralized renewable sources in modern living environments. Prosumerization of the energy landscape: The energy landscape today is becoming increasingly prosumer (production-consumption) based, where energy is produced and stored using decentralized renewable sources. Electric vehicle batteries can be used as a mobile energy storage system that can enable household energy use via

Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) applications [3]. These technologies enable power to flow both ways: energy stored in the battery is used when electricity demand is high, or during days when the tariff to the grid is high. Moreover, the implementation of dynamic pricing schemes for electricity can enable consumers to cut their running expenses by moving electricity use to lower-cost hours. Charging and discharging operations can be intelligently scheduled with adaptive charging strategies based on electricity tariffs, solar energy availability and battery state-of-charge conditions. These measures can help lower the cost of charging, as well as peak demand reduction and stability improvement for energy systems. By incorporating renewable energy generation, bidirectional EV usage, and adaptive pricing, the smart grid residential charging system can offer economic, environmental, and technical benefits, while also contributing to sustainable transportation and energy management goals [4].

The proposed Adaptive Solar-Assisted Residential EV Charging System with Intelligent Energy Management and Vehicle-to-Home Support is an innovative framework to enhance residential EV charging operations. The system includes a solar photovoltaic (PV) array, electric vehicle (EV) battery storage, an interface with the electricity grid, a voltage source converter, and an adaptive control algorithm to optimise energy use and cost-effective charging performance. An intelligent energy management strategy constantly observes the solar energy generation, electricity tariffs, loads at home and battery status to decide the charging and discharging schedule. In low-tariff mode, where electricity rates are low, electricity demand can be met by battery charging to take advantage of available solar and grid energy; In high-tariff mode, where electricity rates are high, electricity demand can be met by V2H operation using battery stored energy. Also, in order to improve the power quality, a least IncoSh based adaptive control algorithm is used to reduce harmonic,

compensate reactive power and near unity power factor operation [5]. The proposed system is designed to enhance overall energy efficiency, minimize electricity costs, maximize utilization of renewable energy and reduce the dependency on the grid. The developed framework is found to be reliable, sustainable and economically viable solution for future smart residential EV charging applications from simulation and performance analysis.

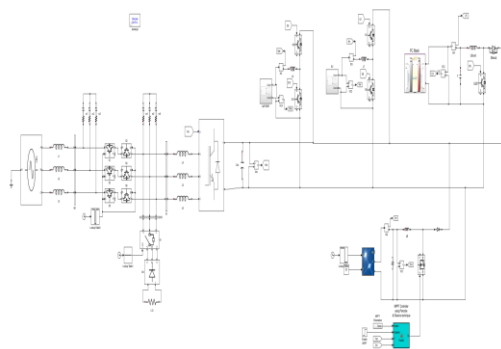


Fig 1 MATLAB/SIMULINK Circuit diagram of the system

One of the key goals of the proposed system is to alleviate stress on the grid during high electricity pricing periods, whilst continuing to provide uninterrupted electricity supply and charging for residents. Figure 5 shows the performance of the system if the price of the utility is high enough above the adaptive threshold and the load demand is suddenly high. In such a manner, EV2 goes to discharge mode instead of charging mode and sends the energy back to the system. Power values that are negative mean charging operation, positive power values mean discharging operation. The simulation results show that EV2 meets the grid requirements, helps the residential loads, and does not interrupt operation of the EV1 charging system. If demand is higher in the grid during these periods of high pricing, then the coordinated contribution from PV generation and battery discharge is able to fill that demand. This mode of operation would avoid

overloading the electricity grid and stressing the network during the peak demand periods. Therefore, the proposed control algorithm can effectively make electric vehicles flexible energy storage means and realize its application in the field of demand-side management. Another key point is that although there is dynamic energy exchange, load reliability does not change. Even though the prices for residential loads fluctuate dramatically, they still receive uninterrupted power.

II SURVEY OF RESEARCH

1. M. Yilmaz and P. T. Krein gave a comprehensive overview of battery charging technologies and infrastructure requirements of PLEVs and HEVs. Several charging topologies, charging power levels, and charging architectures for residential, commercial and public applications were studied. Two methods of charging – conductive and inductive – were assessed in terms of efficiency, rate of charging, method of implementation and flexibility of use. The authors pointed out that the widespread adoption of EVs demands reliable charging infrastructure that can meet the growing demand for charging without compromising grid stability. Several challenges such as transformer overloading, charging coordination, communication protocols, and interoperability among charging standards were analyzed. The paper also explored the potential use of Vehicle-to-Grid (V2G) technologies which enable EVs to be used as distributed energy storage systems. Moreover, the use of renewable energy and smart energy management practices was suggested for enhancing energy efficiency and profitability. The study's findings recommended that future charging infrastructure should include a suite of adaptive control elements, advanced communication networks, and renewable energy sources to enable efficient and sustainable transportation electrification, while also ensuring power quality and system reliability.

2. C. C. Chan gave a comprehensive overview of technologies of EVs and HEVs, covering their development history, working principles, benefits and prospects. Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs) were studied, and their role in GHG reduction and decarbonization of the transportation sector was discussed. A number of battery technologies, such as lithium-ion, nickel metal hydride and lead acid batteries, were assessed in terms of energy density, charging efficiency, battery life and performance. The cost of batteries, a short driving range and the time required for charging are the key challenges to mass market EV adoption, the author said. In addition, the significance of the development of charging infrastructure and advanced energy management systems were highlighted. The paper also emphasized the importance of renewable energy integration for enhancing the sustainability of transportation. Power electronics, battery management systems and charging station rollout issues were extensively studied. The study found that in order to enable efficient, eco-friendly, and economically viable electric vehicle (EV) systems in the future smart energy landscape, there is a need for continuous technology development in batteries, charging infrastructure and integration of renewable energy (RE) sources.

3. S. Deilami, A. S. Masoum, P. Moses, and M. Masoum suggested a smart charging framework that would help to reduce negative impacts of electric vehicle charging on residential distribution networks. This study was focused on peak demand reduction, voltage fluctuation, and transformer overloading due to uncontrolled EV Charging. A decentralized charging coordination algorithm which handles charging schedules according to the network condition, transformer loading limit and user charging requirements was developed. Results of the simulations showed that uncontrolled charging contributed greatly to the peak

demand and negatively affected the performance of the distribution system. The proposed smart charging approach achieved the desired results and reduced voltage deviations and overall grid instabilities without compromising customers' charging satisfaction. It was decided that communication systems between charging stations and EVs would be key to the implementation of real-time charging control. The authors also highlighted the importance of using renewable energy sources in conjunction with charging infrastructure to enhance the sustainability and minimize reliance on utilities. The economic analysis demonstrated the benefits of coordinated charging in terms of lower electricity bills and improved system reliability. This study found that intelligent charging management will be necessary to ensure the performance of the residential distribution network will not be adversely affected when large numbers of EVs are connected to the grid.

4. The authors W. Kempton and J. Tomic proposed the Vehicle-to-Grid (V2G) technology and discussed its use in the existing power systems. The study showed that the battery of an EV can be used as distributed energy storage resources which can assist in the operations of the power grid. Bidirectional charging systems were explored to enable energy transfer from the EV batteries when demand is low, and back to the grid during high demand periods. Applications like frequency regulation, spinning reserve support, peak shaving and emergency backups were studied. The authors emphasized the economic value of the V2G technology, such as the extra revenue that EVs can generate and better use of existing energy resources. Issues on batteries, charging infrastructure, communication and energy management were also addressed. The results from simulation studies revealed that coordinated V2G operation could significantly enhance load balancing performance and decrease the fluctuations of the power system. The research found that advanced control

algorithms and intelligent energy management systems are essential to unlock V2G potential and ensure battery health. This work laid the groundwork for future bidirectional charging systems for smart grid and renewable energy applications for EVs.

5. N. Mithulananthan and K. Y. Lee studied integration of renewable energies in an electric vehicle charging system in a smart grid environment. The study focussed on PV generation systems, battery storage systems and intelligent energy management solutions to enhance sustainability and energy efficiency. Optimization algorithms were developed to coordinate power exchange between renewable energy sources, storage systems, utility grid and EV charging stations. The authors proved that renewable assisted charging is highly beneficial in minimizing dependence on the energy grid, and also in reducing carbon emissions and operational costs. The need for both renewable energy forecasting and adaptive control techniques was highlighted to ensure the reliability of renewable energy systems under varying environmental conditions. The intelligent energy management has been confirmed to enhance the utilization of renewable energy and to aid a stable charging operation through simulation result. Smart grid communication technologies were also identified as an important technology for monitoring and controlling DERs in real-time. The authors found it crucial to integrate renewable energy with adaptive charging methods to realize sustainable transportation electrification and efficient smart grid operation in future residential and commercial charging infrastructures.

6. S. Bacha and H. Turker suggested a PV supply chain for charging EVs by introducing PV energy generation and battery storage devices. The objective of the study was to optimize the use of renewable energy and reduce charging expenses and reliance on

power lines. A smart energy management approach is presented to prioritize the use of solar energy during charging time and optimize the charging schedule of batteries based on the available energy. The various operating scenarios with different solar irradiance, load demand and dynamic charging requirements were analyzed in simulation studies. The results showed that the proposed system was able to significantly enhance energy efficiency and reduce power consumption from the grid. Excess solar power was stored and used when renewable generation was low using battery storage systems. The authors emphasized that solar-powered charging stations can help mitigate the environmental impact of the electric vehicle infrastructure. The authors noted the positive environmental impacts of solar-assisted charging stations, such as decreased carbon emissions and improved sustainability. In addition, the ability of adaptive control techniques to enhance system stability and reliability when environmental conditions change was demonstrated. The study found that solar EVs are a viable approach for the future transportation electrification and smart energy management.

III. WORKING METHODOLOGY

The proposed Adaptive Solar-Assisted Residential EV Charging System with Intelligent Energy Management and Vehicle-to-Home Support will be composed of a photovoltaic (PV) generation unit, electric vehicle battery system, residential loads, utility grid interface, bidirectional power converters, and an adaptive energy management controller. The main goals are to maximize the use of renewable energy, lower charging expenses, decrease reliance on the grid, and enhance power quality. PV array is the main renewable energy source and is used to convert the solar irradiance into electrical energy. A Maximum Power Point Tracking (MPPT) controller is used to harvest the maximum possible power that is available from the solar panels in different environmental conditions. First, the produced solar energy is used to power up the

domestic loads, then the excess energy is used for charging the EV battery. The controller controls the flow of energy, such that if solar generation falls short, then the energy should be taken from the utility grid, or released from the EV battery, depending on the electricity tariff rates and battery state-of-charge (SoC). This smart energy sharing system helps to ensure reliable operation and reduce operational costs and optimize the penetration of renewable energy sources in the residential areas.

The PV system is mathematically modelled and the power generation or energy availability is estimated for different solar irradiance scenarios. The output of PV array is given as:

$$[P_{PV} = V_{PV} \times I_{PV}]$$

The generated photovoltaic power is (P_{PV}), the output voltage of the PV is (V_{PV}) and the output current of the PV is (I_{PV}). The PV cell generates current, which is represented as:

$$[I = I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{NKT}} - 1 \right) - \frac{V+IR_s}{R_{sh}}]$$

The adaptive energy management controller is always monitoring PV generation, household load demand, battery SoC, and electricity pricing information. The charging operations are prioritized in low price periods and Vehicle-to-Home (V2H) functionality is enabled in high price periods to deliver loads to the home from the EV battery. This adaptive scheduling strategy can greatly cut down on electricity expenses and ensure charging availability and customer convenience. By using a Voltage Source Converter (VSC) and an adaptive control algorithm based on least Incosh, the system is able to provide stable operation and power quality. The converter controls the power flow between the utility grid, EV battery, and household appliances. The state of charge equation that describes battery charging and discharging is:

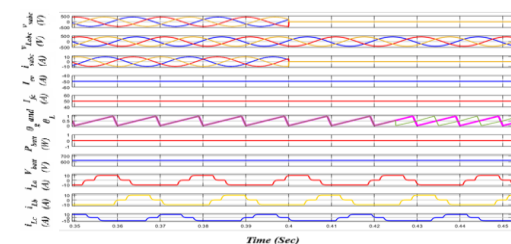
$$[SOC(t) = SOC(t-1) + \frac{P_{ch} \eta_{ch} - P_{dis} \eta_{dis}}{E_{bat}} \Delta t]$$

The symbols (SOC) indicate battery state-of-charge, (P_{ch}) is the charging power, (P_{dis}) is the discharging power, (η_{ch}) and (η_{dis}) are the charging and discharging efficiencies, and (E_{bat}) indicates the energy capacity of the battery. The residential load demand is calculated as:

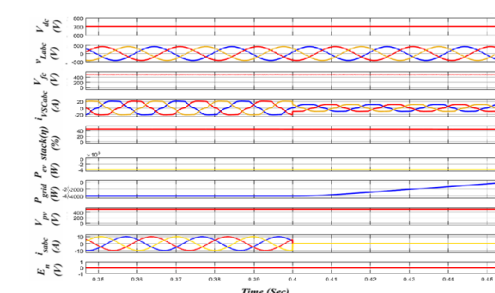
$$[P_{Load} = P_{PV} + P_{Grid} + P_{EV}]$$

where (P_{Grid}) represents the power supplied by the utility and (P_{EV}) refers to the charging/discharging power of the battery. The system has a continuous control of power flow and simultaneously keeps the power factor unity and harmonics suppressed. The proposed methodology shows to be a cost effective, reliable and environmentally friendly solution for future residential EV charging applications when the three aspects of intelligent coordination of renewable generation, adaptive pricing control and bidirectional EV operation are realized.

IV RESULTS EXPLANATIONS



(a)

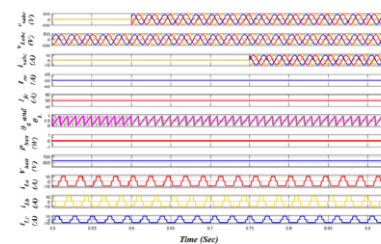


(b)

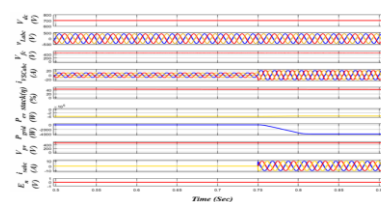
Fig. 2 Mode change from grid-tied to standalone operation for common DC bus EVs charging system.

The system robustness to the fluctuation of the environment was tested by sudden variation of ambient solar radiations while keeping the ambient power export same. Renewable-energy-assisted charging systems are dogged by intermittency of solar power, which directly influences the power available for charging. To validate robustness of the controller, solar irradiance was reduced from 1000W/m^2 to 600W/m^2 , reducing the output power of the photovoltaics from about 5.2kW to about 4kW . Even with this decrease in renewables, the simulation results indicate that there is minimal change to the residential load demand and power exports. The battery storage system and utility power exchange are dynamically coordinated to offset lower solar power generation with the adaptive control mechanism. This behaviour is analyzed and confirms that the proposed controller keeps the system in power balance even in adverse weather conditions. Also, when the load supply is kept constant even though the generation varies, it means that there is good energy scheduling capability. The controller is on duty to constantly check the generation conditions and dynamically change the power-sharing ratio between available sources. When the sun is not available, it only contributes to the grid when needed, maintaining the priority of renewable energy. This is especially relevant for residential charging stations where the weather conditions can markedly impact

charging performance. The results are clearly showing that the adaptive controller is an effective solution to counteract renewable intermittency without disrupting charging efficiency and home supply reliability. Hence, the proposed framework is found to be resilient to environmental shifts, and enhances the stability of operations in realistic renewable generation scenarios.



(a)

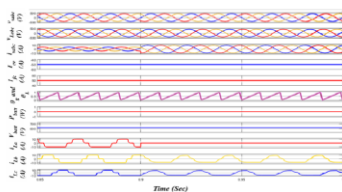


(b)

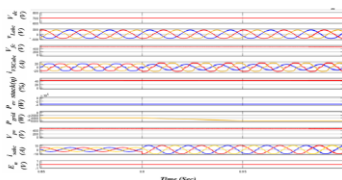
Fig 3 Mode change from standalone grid-tied to operation for common DC bus EVs charging system.

Power quality enhancement capability was assessed by applying the harmonic analysis technique and comparative analysis between various adaptive filtering techniques. The proposed algorithm (Least Incosh) was compared with the conventional methods namely LMS, LMF and SRF under load disturbance conditions. The transient performance and adaptation time to sudden operating changes are compared in Figure 1 and it is shown that the proposed control method is superior. The main benefits of the least Incosh algorithm are its good performance in the

presence of impulsive disturbances and large outliers. The proposed controller dynamically changes Mean Absolute Error optimization to Mean Square Error optimization based on the disturbance conditions, unlike conventional Mean Square Error based methods. This will enhance convergence speed and the immunity to the abnormal operating conditions. The results of this grid current harmonic analysis show that the Total Harmonic Distortion (THD) is around 3.62%, which meets the acceptable limits for power quality. Also, ripples in the extracted load current weights are suppressed quite drastically from conventional SRF techniques. Experimental results show that the ripple amplitude is reduced by almost 60%, which leads to better converter performance and quality of the converted waveforms. The enhanced filtering feature also helps keep unity power factor operation and minimises the reactive power demand on the grid. The findings show the significant system efficiency and converter utilization gains of combining adaptive filtering into the residential charging infrastructure. Therefore, the proposed least Incosh controller results in higher harmonic suppression, less ripple characteristics and better dynamics performance under nonlinear load conditions.



(a)



(b)

Fig. 4 Performance of common DC bus EVs charging system during load unbalancing condition.

Dynamic load behavior analysis was conducted to assess the system stability when the loads are reconnected or disconnected abruptly. In Figures 10 and 11, it can be seen that the voltage stability and power balance of the proposed system is achieved even when the residential load is suddenly increased or decreased. The load current rises quickly from zero when reconnecting the load, and a corresponding compensation of converter interfaces and energy sources must be achieved. The simulation results indicate that the converter current rises to meet additional load and the source voltage remains constant. During transients, the DC-link voltage is kept stable, ensuring an effective energy exchange coordination between the two converters, the PV generation and the EVs' batteries. Likewise, when load is disconnected rapidly, the source current will decrease and so will compensation requirements of the converter. Voltage waveforms are sinusoidal and no significant disturbances are seen in DC-link regulation even after sudden load reduction. The adaptive controller always adjusts the current references based on operating conditions and ensures stable operation during transients. Battery current is also dynamically adjusted with varying demands on the battery without exceeding battery constraints. Importantly, during both load reconnection and load disconnection events, the PV current will not be significantly affected, showcasing good decoupling between renewable generation and dynamic load disturbances. The findings validate the good dynamic stability, power sharing capability and reliability of the proposed architecture under varying operating conditions. Overall, the results of the simulation and experiments are in line confirming the effectiveness of the solar-assisted residential EV charging system to achieve the goal of cost minimization, power quality improvement, maximization of renewable utilization, and robust operation in the face of the realistic residential scenario.

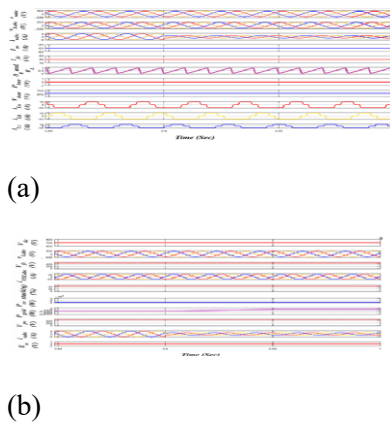


Fig. 5 Performance of common DC bus EVs charging system during variable solar insolation condition.

V.CONCLUSION

The proposed solar-assisted residential electric vehicle charging system with price adaptive control is shown to be a viable solution to the growing challenges of EV charging, integration of renewable energy sources, grid stress and optimization of electricity costs for residential applications. The system developed is successfully assembled with PV generation, home loads, and EVs and achieves reliable and efficient operation in such a way that energy is managed at the most appropriate level based on the environment and operation. Dynamic price-based control optimizes charging patterns based on fluctuating electricity rates, reducing costs and stabilizing the grid during EV charging. The proposed control framework is able to effectively utilize the vehicle-to-home (V2H) functionality during high-demand periods, allowing EV batteries to help reduce household energy dependence on the utility and provide support. The simulations and experiments show that the system continues to be stable with varying solar irradiation, load disturbances, and electricity prices, while maintaining power balance and reliability. In addition, the use of the least Incosh control algorithm shows a significant improvement of the power quality and reduces the harmonics, current distortion and maintains near unity power factor operation. Comparative analysis confirms that the proposed controller is more superior in

terms of faster convergence, better disturbance rejection and better dynamic performance than the conventional approach. The results also reflect better utilization of renewable energy, reduction in grid energy consumption, and better system flexibility.

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