ISSN: 25018

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)

Volume No.12
Issue No. 2
May - August 2025

ENRICHED PUBLICATIONS PVT. LTD

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Design and Analysis of a Micro-Hydro Distributed Power System

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ABSTRACT

The purpose of this study is to improve the standard way of producing electricity in a hydropower plant through the introduction of a more effective method. The aim of installing this Micro-hydro Distributed Power System is to achieve greater results in comparison to those attained with a standard micro-hydro power plant, without depending upon rainfall but upon two stored natural resources, air and water. This air supply will come from solar compressors and the water will be drawn from existing dams or runoff from rivers into storage tanks, which will generate electricity throughout the year at the same rate as the existing micro-hydropower that depends upon rainfall. The Micro-hydro Distributed Power System is a working pressure hydropower plant that generates electricity by compressing fluid into the system, using compressed air and is designed and analyzed in CAD design software and results are calculated to ensure the design is sufficiently durable to withstand the pressure, since the entire power system is dependent upon working pressure and how the power is generated using two major renewable sources, water and air. The Micro-hydro Distributed Power System's working principle has been adapted from hydropower plants, the system converts H-Head(m) into pressure which is then used in the formula in ($P=\rho gh$) to determine the power of the system. Theoretically, the findings of this study prove that the power to be generated, based upon the calculations, is much higher than expected before commencing the research, the power input needed for the Micro-hydro Distributed Power System based upon the compressor system's rated power is 11KW to produce the 13 bars of pressure needed to compress fluid for maximum power output. At 13 bars the compressor system is found to be producing 398.3MW of power but at a high rate of flow of water which is found to be 391.907 L/s. A major advantage of the Micro-hydro Distributed Power System is that this water is pumped back into the tank from which it is re-used over and over again. This system depends entirely upon compressed air which is used to compress fluid through pipes, without this compressed air the water does not flow and cannot be pumped back into the system

Index Terms— Micro-Hydropower plant, Hydropower, Air Compressor, Solar PV, H-Head(m), Water Consumption.

I. INTRODUCTION

A. Motivation and the need for Micro-Hydro Distributed Power System

Micro-hydro Distributed Power System (MHDPS) is an improved hydropower energy source, a renewable energy source that uses compressed air powered by the solar system, and water drawn from rivers/dams where the system is built. It stores water in the storage designed tanks and circulates it around the system generating electricity. In this system, the air is created by the solar compressor to create high-pressured air that compresses water, as it compresses water it creates high-pressure water that is then pushed out at a high speed to turn turbines. This is system is considered to be renewable energy based on the sources it uses to produce electricity mainly water and air. The main purpose of the MHDPS is to provide new ways of producing electricity in a way that will benefit both people and the environment and also have a positive impact on South Africa's economy. The use of air and water to drive the turbine brings many benefits because these two renewable sources will improve the efficiency of the system and the water is also recycled. The MHDPS, as mentioned above, will benefit both people and the environment. It is well known that micro-hydropower plants can be run efficiently and provide clean energy from upstream rivers and do not a reservoir to power the turbine [1]. What makes such power hydropower plants unique is the fact that they do not waste water. Instead, the air pressure is expended to pump back water into storage tanks and re-used to drive the turbine. The standard style pump uses a great deal of electricity and, thus, re-designing it so that it utilizes a renewable energy source to drive the turbine gives a clear indication that the output electric power may be more cost-effective compared to the normal hydropower plants that use electric pumps. This use of pressured air also gives an advantage to the MHDPS by enabling it to control the power output that the turbine produces. The power output depends upon how much air generated pressure is pumped into the water tanks.

B. Literature review

Hydropower is based upon the principle of using water falling from a certain height and flowing water that has an amount of kinetic energy and potential energy associated with it. Hydropower entails utilizing a turbine or water wheel to convert the energy in falling or flowing water into mechanical energy. This energy is then converted into electricity by an electric generator [5].

Micro-hydro power plants are both effective and reliable in terms of generating clean electricity. They can provide electricity from 5KW up to 100KW – a small hydropower plants can provide up to 10MW [1], while the large-scale hydropower plant can produce up to 80 TMW energy. Hydropower plants are of great importance for the current and future electricity systems since they provide electricity without emitting CO2 and hydro reservoirs offer high operational flexibility [6]. Hydropower is one of the most well established sources of renewable energy, providing more than 16% of the world's electricity consumption from both large and small power plants [7]. Hydropower plants do not harm the atmosphere, in fact, their way of producing electricity is very beneficial to the earth, the dams created for such establishments not only benefit humans but also the various species of plants and fish that live in these dams. The use of a solar compressor (whose energy source is the sun) with an improved design that will increase pressure, will enable the enhanced hydropower system to generate more electricity using a smaller amount of water. While many renewable energy sources have a negative effect, hydropower is still the overwhelming leading technology. Nevertheless, in the past years, other renewable energy sources, such as wind power and photovoltaic (PV) have had a much higher growth rate [2]. The MHDPS also uses a PV solar compressor to pump pressure to drive it through the system. Through the introduction of a MHDPS that has no electric pump more results will be achieved. In a normal tested Pump-Hydro unit with two reservoirs, of hydropower capacity of 16 MW, the Pump Power capacity also is 16MW at a fall height of 200m [2], already the pump is consuming the produced energy at that tested 200m. A PHS is a clean and sustainable energy storage system that uses water to store energy. This storage system does not require any chemical substances and can store energy in a wide range of capacities.

It requires two reservoirs of different heights [3]. The difference between the micro-distributed unit compared to the pump-hydro is that it does not use reservoirs of different height but uses them simply to store water and contain pressure that it mixes with air pressure from solar compressors. Hydropower plants are environmentally friendly and do not emit CO_2 , rather, they reduce the CO_2 which is deposited in the surroundings, because of the use of hydropower plants in China it was found that CO_2 emission reduction has passed 70% [8]. The recent shift to a hydropower plant type that uses only a small amount of water, in which water and air are mixed to generate electricity which is equivalent to the standard operated hydropower plant has not been done. The continuous improvement of hydropower plants, involving the use of different solutions and combinations of pipes and storage tanks, has been analyzed to identify the most convenient solutions [9]. Several design options must be taken into account when seeking to create a successful micro-hydro power plant, these design considerations are [5]:
Flow duration curve (FDC)
Flow rate measurement
Weir and open channel
Trash rock design
Penstock design
Head measurement
Turbine power
Turbine speed
Turbine selection
From the above options for a micro-distributed power system, only certain items must be considered since pressure created by the compressor eliminates most of the above items. The items to be considered

are: Flow duration curve (FDC), Flow rate measurement, Turbine power, Turbine speed and Turbine selection, as well as pipe design with pipe selection for better flow. Compressors are used widely globally, machines such as grinders and even drillers that previously utilized electricity, now are designed to use air as their source of energy. The redesigning of a pump that will use air from the solar compressor to create pressure will make the process of the pump use less electricity and the input will not be equal to the output. Centrifugal compressor which is of a small size, a simple and compact structure and a high single-stage pressure ratio, has been widely used in small and medium-sized turbo aircraft engines and almost all types of auxiliary power plants. The optimal design of a centrifugal compressor with high-pressure ratio and deficiency in air equipment tool has been the pursuing target of compressor designers for decades [10].

C. Contribution of the system

Small hydropower is one of the renewable energy technologies that have great potential within the Sub-Saharan African region, with a high potential of improving quality of life (12).

Almost a fifth of the world's electrical supply depends on potential energy, and the government has seen hydroelectric dams as a means of stimulating economic growth through the provision of clean energy(13). Since Micro-hydro The advantages of a micro-hydropower plant over the same size wind, wave and/or solar power plants are [1]:

- High efficiency of 70%-90% and, thus, by far the best of all energy technologies.
- High capacity factors of >50% compared with 10% for solar and 30% for wind power plants.
- A slow rate of change; the output power varies only gradually from day to day and not from minute to minute.
- Power output is maximum in winter.

This system will not only contribute to providing electricity but also to the conservation of rainwater since the storage tanks will be drawing water from the nearby dams or rivers which will then be used or be benefiting in farming. South Africa’s economy also depends on farming, and the agriculture sector is one of the main pillars of the country's economy and is one of the largest sectors that consumes water, with about 62% of the annual useable runoff rainwater (14). This system is going to contribute to the energy sector, agricultural sector, and the improvement in the small hydropower generating method.

II. PROCESS FLOW

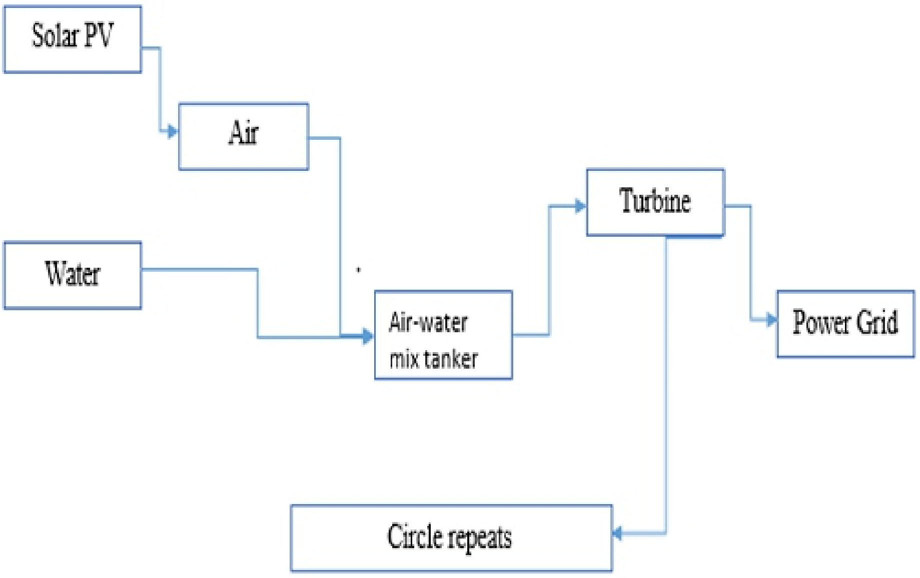

Figure 1 a simple flow chart

The use of air and water has been done and analyzed in form of exploitation of low-head hydropower by pressure interchange with air, using siphons, with careful design of the flow passages to minimize losses, air-pumping efficiencies of 70 percent (15). Applying the principle of air pressure and using that air pressure to push water at high speed, without considering the siphons and using different designs to produce more power is what the diagram shows.

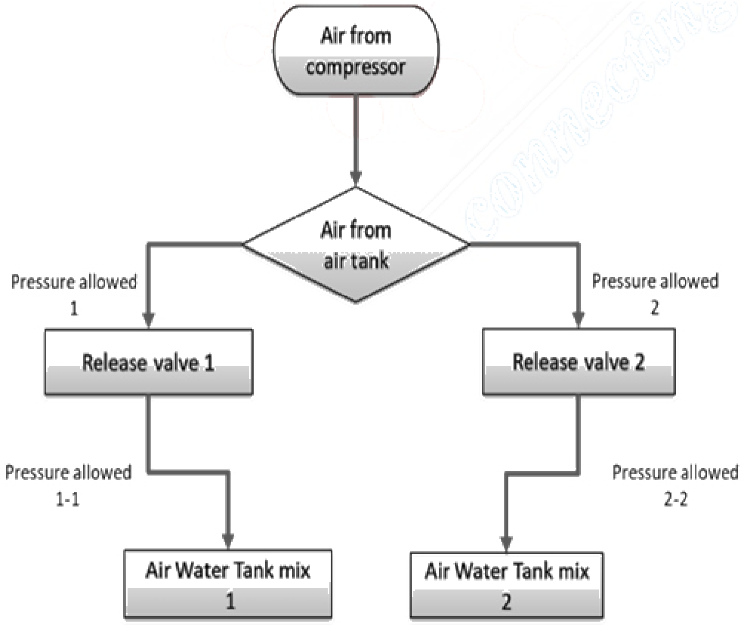

Figure 2 Air process from a compressor to mixing with a water tank

Table 1 Pressure Release work process

Working pressure on a pipeline to Release Valve 1	3bar	3bar	Working pressure on a pipeline to Release Valve 2
	0bar	0bar	
Pressure allowed 1	yes	no	Pressure allowed 2
	no	yes	
Pressure allowed 1-1	yes	no	Pressure allowed 2-2
	no	yes	

The label “Pressure allowed” in Figure 8 above indicates that the valve allowing pressure is open, as shown by yes (green) and when the required pressure is reached, it closes that main release valve 1 and opens release valve 2. The main purpose of the release valve for the MHDPS is to allow and reject the air needed to the mix tank and to allow or reject the air (pressure) needed on release valve 1, since this release valve does not work simultaneously wih release value 2. If release valve 1 is working and needs 3000 Kpa, release valve 2 will not work during that time. As soon as release valve 1 has acquired the allowed pressure of 3000 KPA then the release valve 2 will repeat the process that with release valve 1. Before release valve 1, there is a computerized valve that allows the change of pressure to be directed to a single line on release valve 1, this process is termed the “breathing method”.

III. DESIGN ANALYSIS

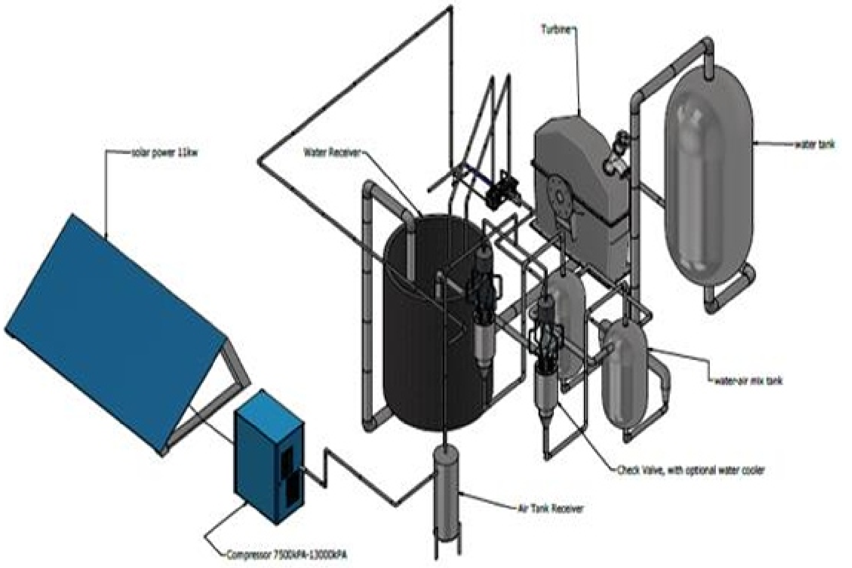

Figure 3 3D View of Micro-hydro Distributed Power System

This **air tank** is an air receiver, it accepts air from the pumps and compressor and discharges the air to the check valve. The air tank is used to store air at a higher pressure than what is needed for the MHDPS and creates a favourably high pressure when it is needed for the system [11].

The **released valve design**, only allows air to pass through, it doesn't allow air to flow back, or reverse pressure. The release valve at certain pressure releases air to the other tank. And when the pressure is reached its maximum operation point it goes to the other release valve to do the same process at release valve 1. Refer to Table 1 Pressure Release work process.

The **air-water tank**, allows air to build up as it creates high pressure, the reason for two air-water tanks is to allow each tank to clear, for water which will be pumped in to be pumped in without a push back pressure which will make the water fill in slow. The principle to this is the breathing method as one release valve releases, the other release valve is working on filling the tanks.

Theoretical pressure will always be the same as per a single release valve, with the assumption that in the process of the working release valve there are no pressure losses which are due to:

- Leakage of a pipeline.
- Valve leakage
- Friction losses
- And other minor unplanned losses which might occur.

The main pressurized tank, the main pressurized tank is the last in the process of this power system, which discharges the pressure created by the air-water tank. The water comes at high pressure, which is then directed to the turbine.

Water Reservoir, collects water from the river or dam and water from turbines after generation process is pumped back to this Water Reservoir,

Pumps

Pumps are custom made for this power system, it uses air. The air used in the pumps is air from the Air-Water tank-mix which is released into the pumps. The pumps are also responsible to pump water to the Air-Water tank mix. There is also an optional pipeline in the case where the pressure from the Air-Water tank mix is not meeting the required pressure to pump water into the tanks. The optional air pipe is from the main compressor tank that will supply Air from the compressor to the Pumps.

Pump working principle

- **Water to Reservoir tank (Main water Tank)**

Water is drawn from the river or nearby stream/dam to the first tank, as water is passing through Air vanes water is drawn by Water vanes to the Reservoir Tank. The Reservoir Tank is an open tank, the pressure on top is atmospheric (101.323KPA).

- **Water to Air-water Tank Mixture**

Water is pumped again to the Air-water Tank Mixture at a lower pressure when check Valve A is open, Check Valve B is closed allowing water in at lower pressure, as soon as water required is in the Air-water Tank Mixture B, Pumps stop working on Air-water Tank Mixture A, and move to pump water at Air-water Tank Mixture B, pumping water at the same rate, and same conditions from Air-water Tank Mixture B. this process is the working principles of the Air-water Tank Mixture A and B.

1. Off-shelf sources.

GA-11 compressor is an oil-injector rotary screw compressor type. The calculations used to determine how much pressure is needed and how much power will this power system needs are referenced from this **GA-11 Compressor**. The other reason to consider an oil-injector rotary screw compressor type is this compressor type has only two moving parts compared to the piston air compressor which has many moving parts. And the rotary screw compressor operates at lower temperatures and has a good cooling integrated system (16).

solar energy for the design Micro-hydro power system must be able to provide 11KW to 25KW for effective production or desired air at all times, for both air tanks and pumps. The air will be recycled during times when the system needs to be strained. Solar energy must meet the demand. Compressor selected needs a minimum of 11KW to produce 7bars to 13 bars, solar energy between 11kw to 25kw will allow the power system to have access energy which will also be used as for back up to the system and to other electrical components the power system requires.

The homer is the most popular tool for sub-national level planning energy distribution, The software has been extensively used in many studies for a cost comparison of investment decisions (17). Homer reduces the complexity by producing worldwide databases for solar PV radiation and the ability to design and choose industrially available components, and the option to model PHS as a storage type along with other technologies (18). Using the software to simulate how much power can I extract from the all-season climate, will help in deciding how much solar PV and storage I need for the system.

Kaplan Turbine is a reaction turbine type that Micro-hydro Distributed Power System will run with, Kaplan Turbine allows water to flow both in and out in the axial flow. What makes the Kaplan Turbine during the demand is the blades can be changed angle for maximum efficiency for different flow rates of water (19)

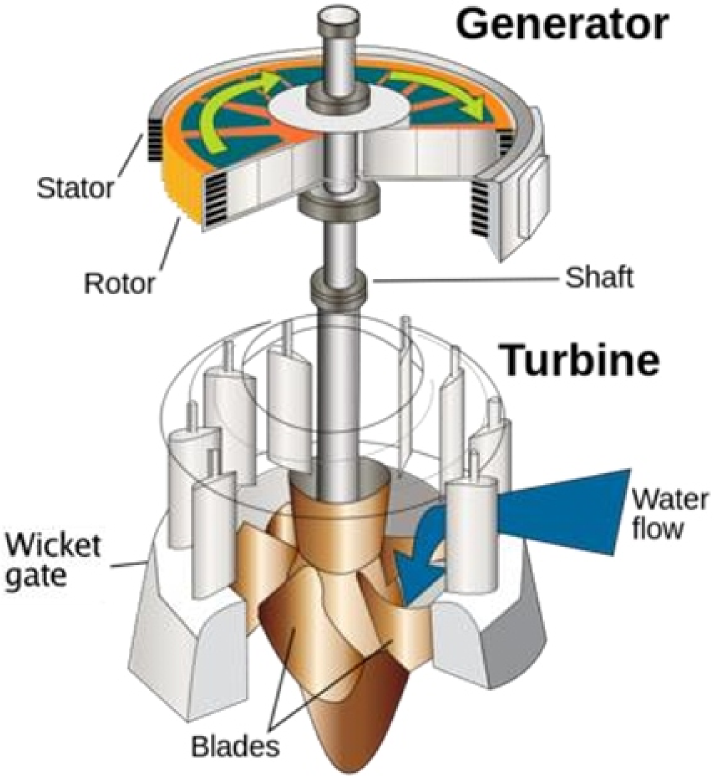

Figure 4 Kaplan turbine (19).

Since water has to be in axial flow, the water from the turbine will enter the turbine in radial flow. Kaplan's design is different compared to other turbines, it allows water to first enter through radial then exit axial unlike other turbines (20). This will not anyhow make water to turn the turbine lose pressure because the water in the line to the turbine is already pressure raised from the water-air tank mixture.

IV. RESULTS

Pressure in the water is to Pressure Head (H).

H_{net} is the gross head and head losses can be assumed to be

10% (21).

$H_{net} = H_{gross}$ X0.9

or

$H=\frac{P}{\rho g}$

The efficiency being used is in reference to some conducted experiments on the small hydropower plant since generating of the power was not practically done.

Therefore, the overall efficiency of a small hydropower plant is found to be its drive efficiency is 95%, generator efficiency is 93%, and turbine efficiency is 85% (21).

Therefore the overall system efficiency of small hydropower which is the Micro-hydro Distributed Power adapted will be as:

$\eta_{\text{overall eff}} = \eta_{\text{Drive eff}} X \eta_{\text{Generator eff}} X \eta_{\text{Turbinel eff}}$

$=0.95X0.93X085$

$=0.75$ or 75%

Mass flow rate ($\dot{m}$) = l^{-1} or kg^{-1}

Therefore the power output base on different heights will use the following formula

$P_{\text{power}} = \dot{m} X H_{\text{net}} Xg X \eta_{\text{overall eff}}$

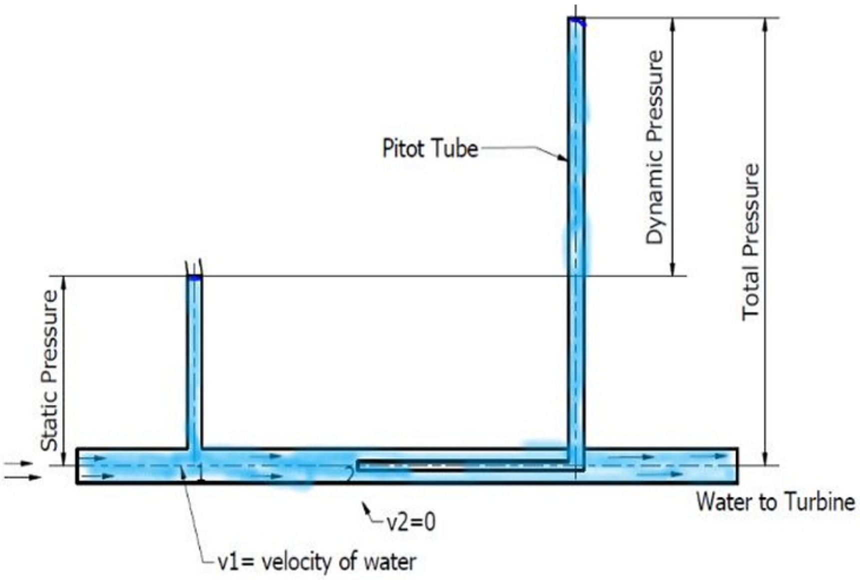

Figure 5 Velocity of fluid to the turbine.

Benoli Equation

$$\frac{P1}{pg} + \frac{V1^2}{2g} + Z1 = \frac{P2}{pg} + \frac{V2^2}{2g} + Z2$$

Z_1 and $Z_2= 0$

P1 =(Ps) static pressure

P2=(Pt) (total pressure)

$$\frac{P1}{pg} + \frac{V1^2}{2g} = \frac{P2}{pg}$$

$$P1+\rho\frac{V1^2}{2g}=P2$$

$$V1^2=\frac{2(\text{pt}-\text{ps})}{\rho}$$

Table 2 Pressure supplied by the compressor and generation of power

P(kpa)	volume flow	power(W)	Power(MW)
0	0	0	0
50	0	0	0
100	74.48118	8660.34155	0.00866
150	108.2402	16644704.3	16.6447
200	133.7328	25579810.5	25.57981
250	155.0901	35480837.6	35.48084
300	173.8432	46290196.8	46.2902
350	190.7615	57948691.9	57.94869
400	206.297	70404135.4	70.40414
450	220.7419	83611621.6	83.61162
500	234.2978	97532458.9	97.53246

V. DISCUSSION

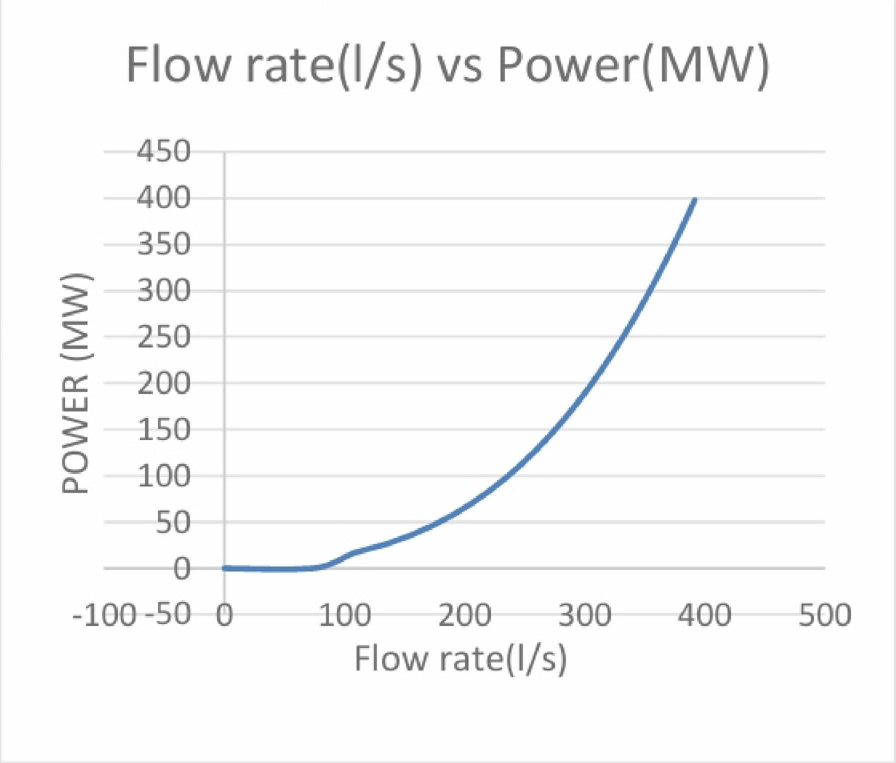

Figure 6 Water consumption vs power production

According to the calculation and graph presented, the greater the power output, the more water is needed in the system as the pressure increases in the air-water tank (air compressor filling the release valve). From 0L/s to 75L/s, as indicated in the graph, theoretically there is no power being generated due to Pressure P from Table 1 of the theoretical calculation being pressure from the compressor, Ps is static pressure and Pt is the total pressure inside the water-air mix tank, Table 9's theoretical calculation from the main table, the zeros(0) from dynamic pressure to Power.

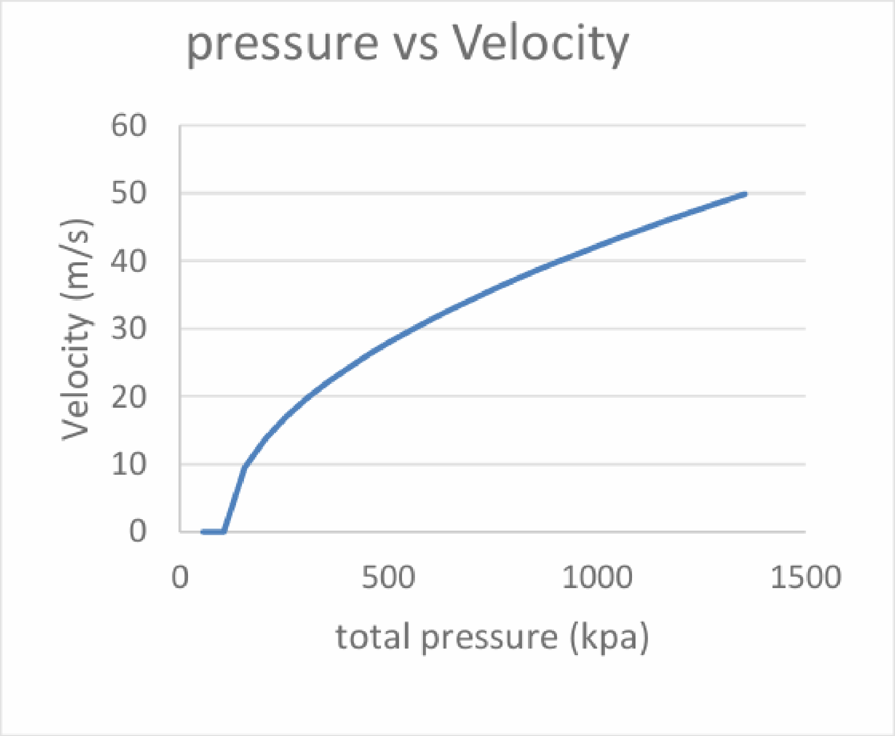

Figure 7 Pressure(kpa) vs velocity (m/s)

The pressure created in the main pressurized water storage exits the tank at high speed to the turbine, and as the pressure increases the velocity of water increases, and more pressure is added the greater the flow rate.

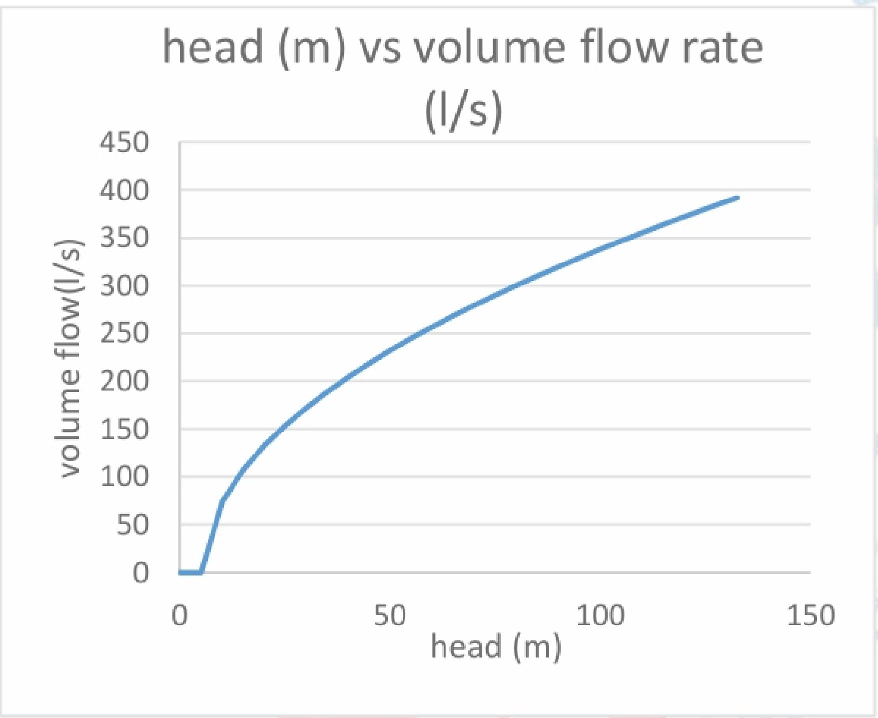

Figure 8 Head (m) vs Volume flow rate (l/s)

This graph shows a pressure converted to a pressure head (m)from a hydro pressure (P=ρgH) used to calculate the height. For instance, if 555.0341 KPA for this pressure the head is 50.9684m, the more head increases the more this power system uses or discharges water to the turbine.

VI. CONCLUSION

The MHDPS represents theoretical research undertaken with a design to support the theoretical results. It was proposed originally as falling under the category of the small hydropower plant, but due to the results obtained, it can be categorized as a large power plant. The only problem with the MHDPS is the amount of water it consumes while producing electricity, bearing in mind that the more the flow rate the greater the electricity generated. To solve the water crisis associated with the MHDPS, the design is designed to recycle water by using air pumps to drive the water back into the system. At 13 Bar pressure from an 11KW rated solar compressor, 398MW of electricity theoretically can be produced from the proposed MHDPS.

As stated and shown above 398MW is a theoretical calculation, and the efficiency of the generating stage is not calculated for the said MHDPS due to the research not being implemented practically. The overall efficiency used for this system is of a small hydropower plant that was used based upon the initially proposed idea that this system will be categorized as a small hydropower plant, based on the nature of the design and capacity of the source (solar energy for compressor, size of compressor and the amount of water needed to operate the envisaged MHDPS).

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ISSN: 25018

Novel Control Technique for DC-DC Buck Converters with Parametric Uncertainties

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ABSTRACT

In this paper, a novel control technique i.e., Single-loop Adaptive Control (SA) for DC-DC buck converters is proposed. Initially, the nominal system of the DC-DC buck converter without considering the parametric uncertainties is built to develop the SA. Adaptive and back stepping control approaches are used to build the proposed technique. The proposed control strategy is analyzed for load variations and also for change in reference voltages. The advantages and disadvantages of the proposed control strategy are compared, analyzed and a conclusion is drawn.

Index Terms— Adaptive, back stepping approach, Parametric uncertainties, Single-loop Adaptive Control (SA)

I. INTRODUCTION

DC-DC converters are widely used for power conversion applications such as, electrical equipment used in medical systems, Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV), power supply and portable recharging systems. As there are numerous applications, the requirements for output voltage vary from application to application [1] – [3]. Also, the requirement for converters differs as well, so as to achieve faster dynamic response or to decrease the ripples in the output voltage, while some require a stable output voltage even in the presence of load variations and parametric uncertainties. Thus, the focus of the industries and scholars has been to design a converter which satisfies the requirements of all the applications. Typically, the control structure presented is single loop control structure. The other type of control structure is double loop control structure [4]. The advantages of single loop control structure over double loop control structure is its simple implementation; also that current measurement is not required and hence, single loop control is also known as direct output control or voltage mode control. Whereas, a double loop control structure has two loops i.e., voltage regulation loop and current tracking loop and this control is known as indirect output control. It has strong anti-interference ability as it allows internal loop to control disturbances before affecting primary control objective [5].

Though double loop control can improve the system dynamic performance and tighter control, it is way more complex compared to single loop control as it needs to measure current also [6]. Based on single and double loop control structures, several control techniques have been proposed during the course of time [10] - [15]. To control buck converters, some linear control techniques were designed based on the linear modelling [16]. But, it is known that, the traditional linear controllers have worse dynamic performance compared to nonlinear controllers [17]. Some of the linear control techniques applied to the DC-DC buck converters are Traditional Sliding Mode Control (SMC), Second order sliding mode control for output voltage regulation [7] – [9], [13]. Double loop control structure SOSM controllers are designed containing voltage regulation loop and current tracking loop [22]. They are well known for their good tracking performance and Disturbance rejection ability against parametric uncertainties and external disturbances [13]. Adaptive control techniques [5], [20], [21] and fuzzy controllers are some of the other suitable techniques. In one of the adaptive control techniques, adaptive finite time control algorithm, voltage regulation time has been enhanced by using two finite time convergent observers to estimate unknown input voltage and load variations [23].

Though these non-linear control techniques improve the performance of the converter, most of them assume nominal values of filter inductor and output capacitor same as their actual values which effects the control performance of converter system as parameter uncertainties exist in practice. Though the control strategies such as SOSM and intelligent control algorithms show high performance, they are not highly recommended for being highly non-linear, complicated and having many control parameters making them difficult to analyze, design and implement. Few works have evaluated the performance difference between the both type of control structures through experiments too. Thus, the main contribution of this paper is to design control strategy, model of the system with and without considering parametric uncertainties in order to design the proposed Single loop adaptive control technique. The objective is to regulate output voltage to its desired reference voltage in presence of unknown disturbances and parametric uncertainties. By focusing on this objective a simple yet novel control technique i.e., Single Loop Adaptive Control Strategy has been designed based on the adaptive and back-stepping control approaches.

II. STATE SPACE REPRESENTATION OF DC-DC BUCK CONVERTER MODEL

The parameters of the DC-DC buck converter as shown in Figure. 1 are: v_{in}, the input voltage, L is the filter inductor, C is the output capacitor and R is the equivalent load considering the unknown disturbance.

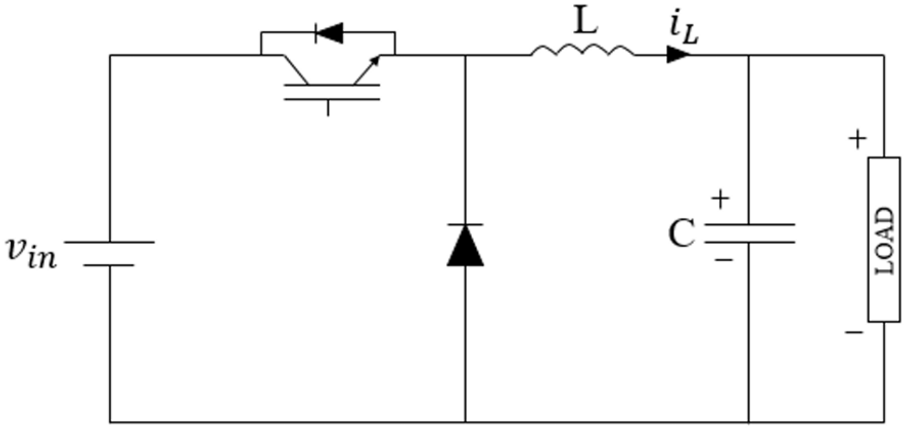

Figure. 1. DC-DC BUCK CONVERTER

When the switch is ON, by applying KVL we get,

$$\boldsymbol{v_{in} = L\frac{di}{dt} + v_c} \qquad (1)$$

When the switch is OFF, by applying KCL,

$$\boldsymbol{i_L = i_c + i_o} \qquad (2)$$

Where, $\boldsymbol{i_c = C\frac{dv_c}{dt}}$ and $\boldsymbol{i_o = \frac{v_o}{R}}$

By considering output voltage $(V_c)ax_1$, current through inductor (I_L) as x_2, control input as uav, The averaged model of the DC-DC buck converter in continuous conduction mode (CCM) can be expressed as follows:

$$\boldsymbol{\dot{x}_1 = \frac{x_2}{C} - \frac{x_1}{RC}} \qquad (3)$$

$$\boldsymbol{\dot{x}_2 = -\frac{x_1}{L} + \frac{v_{in}}{L}u_{av}} \qquad (4)$$

It is to be observed that for the sake of simplicity, Discontinuous Conduction Mode (DCM) is not considered. The above system (3) - (4) is the nominal system for the converter without considering the parametric uncertainties of the filter inductor and output capacitor. Considering the fact that some practical applications do not know the accurate values of inductor and capacitor, the actual values of inductor and capacitor are defined as follows:

$$\boldsymbol{\bar{L} = L + \Delta L, \bar{C} = C + \Delta C} \qquad (5)$$

Where, L and C are nominal values and ΔL and ΔC are parametric uncertainties (unknown values) of filter inductor and output capacitor respectively.

Thus the DC-DC buck converter with uncertainties can be written as,

$$\boldsymbol{\dot{x}_1 = \frac{x_2}{\bar{C}} - \frac{x_1}{R\bar{C}}} \qquad (6)$$

$$\boldsymbol{\dot{x}_2 = -\frac{x_1}{\bar{L}} - \frac{v_{in}}{\bar{L}}u_{av}} \qquad (7)$$

By the dynamics of the converter, (6) and (7) can be rewritten as:

$$\dot{x}_1 = \frac{x_2}{C} + d_1 \qquad (8)$$

$$\dot{x}_2 = -\frac{x_1}{L} + \frac{v_{in}}{L} u_{av} + d_2 \qquad (9)$$

Where, $d_1 = -\frac{\Delta C x_2}{C(C+\Delta C)} - \frac{x_1}{R(C+\Delta C)}$ and $d_2 = -\frac{\Delta L x_1}{L(L+\Delta L)} - \frac{\Delta L v_{in} u_{av}}{L(L+\Delta L)}$

The State Space Representation of the converter can further be expressed in the form of,

$$\dot{x} = Ax + Bu_{av} + d$$

$$\text{i.e., } \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{v_{in}}{L} \end{bmatrix} u_{av} + \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \qquad (10)$$

Where, $= [x_1 \; x_2]^T$, $A = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{C} & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ \frac{v_{in}}{L} \end{bmatrix}$, $d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$

As the objective is to regulate the output voltage to its desired reference voltage even if unknown disturbances and parametric uncertainties are present, based on the above dynamic model, Single-Loop Adaptive Control strategy will be designed to achieve the control objective. Before proceeding, the following lemma is presented.

Lemma 1: [25] If $\mathbf{F} \in \mathbb{R}^{n \times n}$ is the Hurwitz matrix, then there exists a positive scalar $\in$, such that $\|e^{Ft}\| \leq \in e^{\frac{\lambda max}{2} t}$ where , where $\lambda_{\max}$ is the largest eigenvalue of **F.**

III. STATE SPACE REPRESENTATION OF SINGLE LOOP ADAPTIVE CONTROL STRATEGY FOR NOMINAL SYSTEM

Based on the nominal system (3) - (4), the Single Loop Adaptive Control strategy is designed to achieve the control objectives. The error in obtaining desired output voltage,

$$z_1 = x_1 - x_1^*$$

Where, x_1^* = desired output voltage

Where, x_1^* = desired output voltage

From equations (3) and (4), $\dot{z}_1 = \frac{x_2}{C} - \theta x_1 - x_1^*$

Where, $\theta = \frac{1}{RC}$ (Unknown parameter)

For load variation, let us assume that equivalent load *R* known and changes in steps. By defining $\bar{\theta} = \hat{\theta} - \theta$ Lyapunov function can be constructed, $v_{s11} = \frac{1}{2} z_1^2 + \frac{1}{2\eta} \tilde{\theta}^2$

Where $\hat{\theta}$ = adaptive law to be designed. By differentiating above equation,

$$\dot{v_{s11}} = z_1\left(\frac{x_2}{C} - \theta x_1 - \dot{x}_1^*\right) + \frac{1}{\eta}\tilde{\theta}\dot{\tilde{\theta}}$$

From above equation, one can design as follows: virtual control $\alpha_1 = -k_{s11}z_1 + \dot{x}_1 + \hat{\theta}x_1$; error variable $z_2 = \frac{x_2}{C} - \alpha_1$ and adaptive law $\hat{\theta} = -\eta z_1 x_1$; where, k_{s11} & η are two scalars.

By substituting the value of x_2, $\dot{z_2} = -\frac{\dot{x_1}}{LC} + \frac{V_{in}}{LC}u_{av} - \dot{\alpha_1}$

Lyapunov function v_{s12} for error system, $z = [z_1, z_2]^T$ *is* $v_{s12} = v_{s11} + \frac{1}{2}z_2^2$

$$\dot{v_{s12}} = -k_{s11}z_1^2 + z_1 z_2 + z_2\dot{z_2}$$

$$= -k_{s11}z_1^2 + z_2\left(z_1 - \frac{x_1}{LC} + \frac{v_{in}}{LC}u_{av} - \alpha_1\right)$$

The control u_{av} such that $\dot{v}_{s12} < 0$, $u_{av} = \frac{LC}{v_{in}}(-z_1 + \frac{x_1}{LC} + \alpha_1 - k_{s12}z_2)$

$\dot{v_{s12}} = -k_{s11}z_1^2 - k_{s12}z_2^2 \leq 0$ **i.e.,** the error system $(z_1, z_2) \to 0$ i.e., the controller can regulate the output voltage to its desired reference.

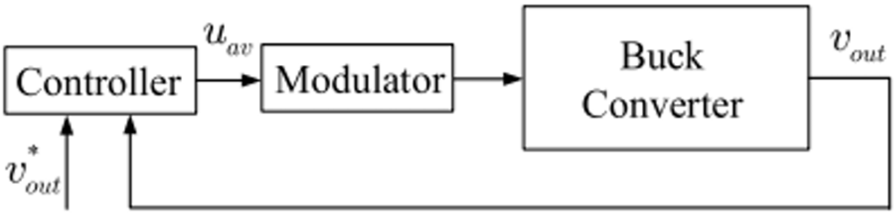

Figure. 2. Block diagram of Single-Loop Adaptive Control Strategy

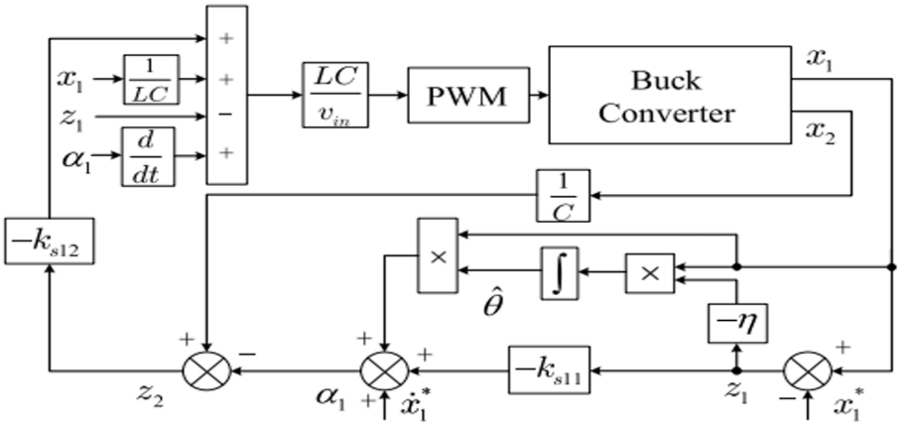

Figure. 3. Control Structure of SA control strategy

I. NOMINAL PARAMETERS OF THE BUCK CONVERTER

Description	Parameter	Nominal Value	Units
Switching frequency	f_{sw}	15	KHz
Inductor	L	$38.7 \text{ x } 10^{-3}$	H
Capacitor	C	$8.33 \text{ x } 10^{-4}$	F
Load Resistance	R	20→10	Ω
Input Voltage	V_{in}	340	V
Reference Voltage	x_1^*	72→55	V

II. CONTROL PARAMETERS OF THE PROPOSED CONTROL STRATEGY

CONTROL PARAMETER	VALUE
η	1200
K_{s11}	150
K_{s12}	200

IV. SIMULATION RESULTS

In this section, the results obtained for the proposed strategy to control the output of DC-DC buck converters are analyzed. The nominal parameters of the buck converter and the control parameters of the proposed control strategies are presented in I and II, respectively. The control objective is to regulate the output voltage and the results are given for two cases: load resistance and reference voltage variations.

A. Load Resistance Variations:

In this, the aim is to maintain the output voltage constant even during load variations. Thus, the reference voltage is kept constant at 72V and the load resistance is changed from 20Ω to 10 Ω. Through the results obtained, it can be seen that the proposed control strategy can regulate the output voltage to its reference voltage even under load variations. As shown in Figure. 4, the recovery time is 60msec and the voltage ripple is 160mV. Here, the voltage drop is less due to the adaptive law which adapts the unknown parameter, $\theta = \frac{1}{RC}$; Also the recovery time is very less and it has a faster dynamic response.

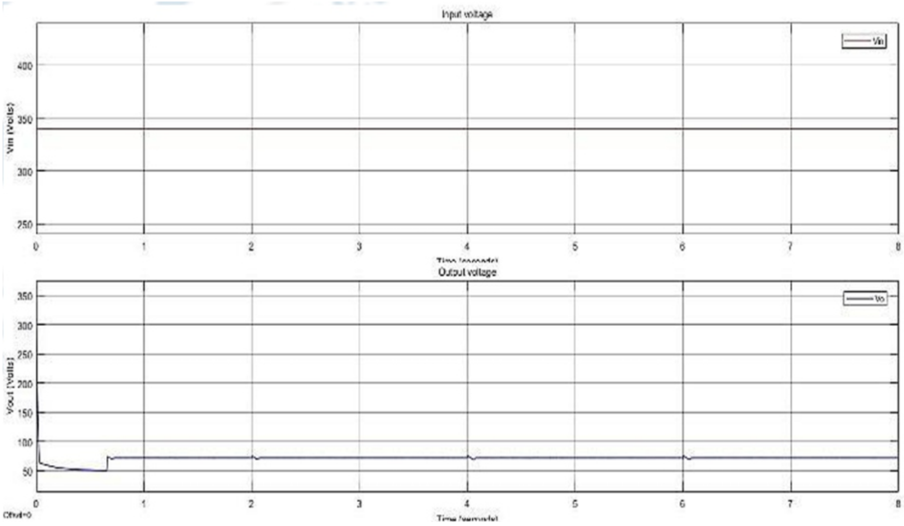

Figure. 4. Simulation result for load resistance variations

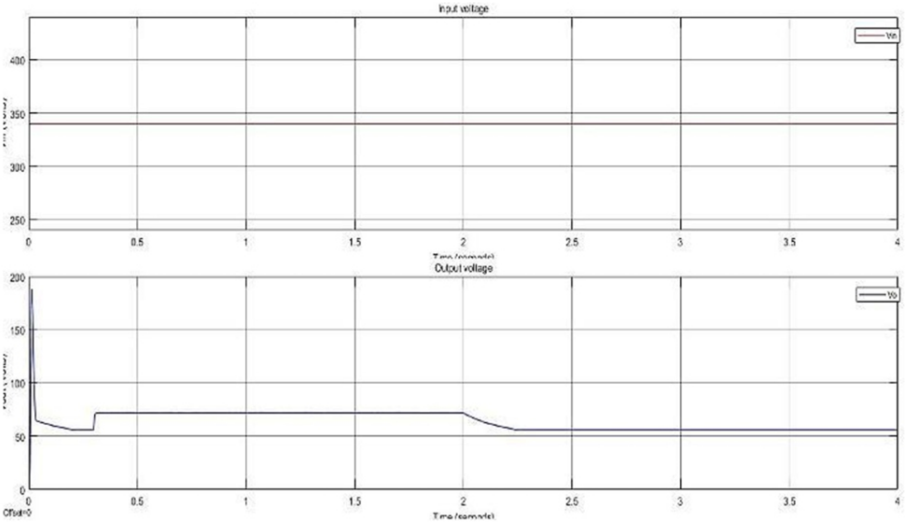

Figure. 5. Simulation result for voltage reference variations

B. Reference Voltage Variations:

Here, the reference voltage is changed from 72V to 55V while the load resistance and control parameters are kept constant. As shown in Figure. 5, when the reference voltage is changed, the voltage undershoots and recovers to its new reference voltage. Here, the recovery time is 250msec and ripple voltage is 130mV.

Therefore, the proposed Single Loop Adaptive control strategy can be used for the DC-DC buck converter to achieve the best performance in applications which require fast dynamic responses when the load or reference voltage changes.

V. CONCLUSION

The problems associated with regulation of output voltage in a DC-DC buck converter has been investigated in this paper. Based on the nominal and uncertain systems of the DC-DC buck converter, a novel control strategy, Single loop adaptive control strategy has been proposed. The characteristics and design procedure of the control strategy are discussed and analyzed. The results of the load resistance variation and the reference voltage variation, are provided to further analyze the advantages and disadvantages of the proposed strategy. The SA can ensure that the output voltage has the shortest recovery time whenever the load or the reference voltage changes. On the other hand, how to design an efficient controller for DC-DC buck converters considering the practical inductor and capacitor with parasitic resistances is still an open problem.

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ISSN: 25018

Enhanced Model Predictive Control for V2G Enabled Grid Using Z-Source Inverters: A Comparative Analysis with ANN Integration for EV

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ABSTRACT

The paper postulates a new approach in energy management through 'Vehicle-to-Grid' in the context of the micro-grid where the Electric Vehicle battery acts as storage for both storing and supplying energy from a DC fast charger architecture. This system allows a bi-direction flow of energy between the Grid and the Vehicle for active power stability management in the context of energy demand management in the micro-grid setting. A Model Predictive Control strategy incorporated with Artificial Neural Network enhances responsiveness, stability, and the power quality of the system by reducing harmonic distortion in the grid-injected current. Simulation results have been quite robust in dynamic performances that signify the possibility of increasing micro-grid resilience and V2G-enabled grid-connected EV systems.

Index Terms— Model Predictive Control, Z-Source Inverter, Electric Vehicle Systems, Artificial Neural Network, Variable Cut-Off.

I. INTRODUCTION

Electric Vehicles Transitioning into Electric Vehicles seems to be an exciting move toward sustainable energy with EVs holding promise for using their batteries for effective energy storage. When plugged into charging stations, Evs can self-recharge while feeding power back into the grid to participate in energy management in micro-grids. V2G technology is a very useful solution, which can enable power flow in both directions and charge during low demand and discharge during peak demand. Integration with renewable energy sources is possible to achieve peak shaving, voltage regulation, and energy stability in micro-grids. This paper examines a DC fast charging station model for V2G within a micro-grid, using off-board chargers and grid-connected inverters for seamless power exchange. This implies that with the proposed MPC strategy aimed at optimizing dynamic performance and reducing disruptions in the power grid, the approach will be improved with an ANN. This study focuses on finding a balance in achieving effective voltage stability along with the regulation of the active power through the MPC-ANN integration towards improved energy efficiency and stability within grid-connected EV systems.

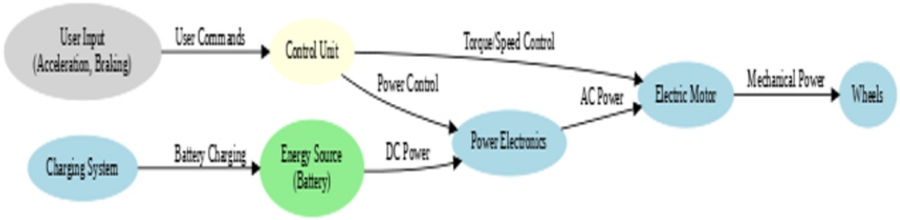


Figure 1. Basic EV System Elements

This figure presents the elements and operation of a basic EV system.

On the other hand, the efficiency of EV systems is influenced by the power management and control systems. Variations in load demands, state of charge of the battery, and interactions with the grid may affect the stability and efficiency of EV operations, and therefore sophisticated control strategies are required. Quick response to changes in load demands and ability to stabilize the voltage and current outputs of power management are crucial to optimizing EV performance under varying operating conditions.

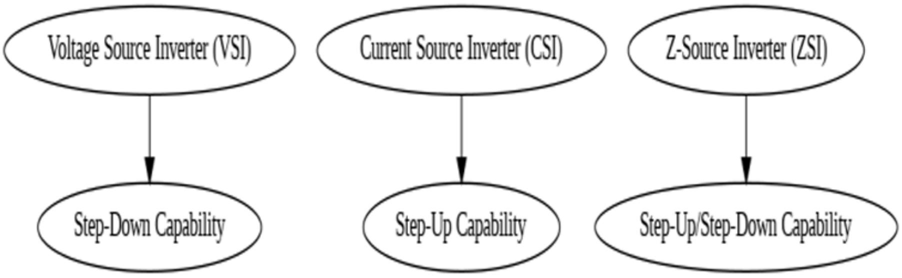


Figure 2. Comparison of Inverters This Figure compares the characteristics and functionalities of different types of inverters, including VSIs, CSIs, and ZSIs.

Two categories of inverters are largely used in a conventional EV system: VSIs and CSIs. In the case of VSIs, the DC is stepped down from the batteries and is converted into an AC power suitable for the EV motor. On the contrary, CSIs can only step up the voltage and therefore are not very flexible for applications in EV systems that require both step-up and step-down functions. ZSIs have been developed to overcome this limitation, with the ability to perform step-up and step-down functions through an impedance network called Z-network placed between the DC source and the inverter circuit. This functionality makes ZSIs highly suited for EVs, whose load requirements may vary a lot during driving and charging.

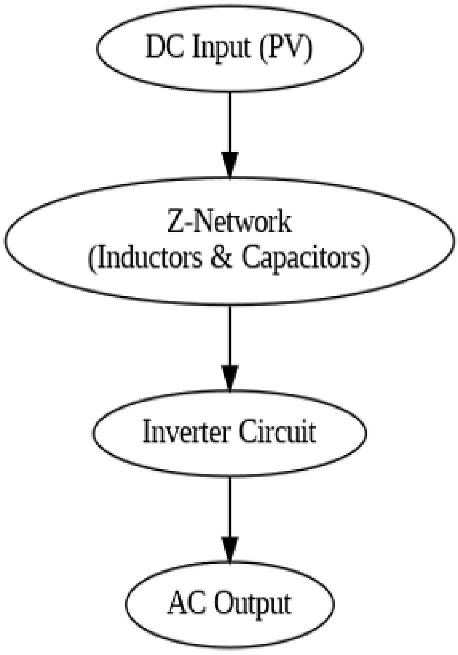


Figure 3. Z-Source Inverter Circuit This Figure presents the circuit configuration of a Z-Source Inverter.

This feature of handling variable voltage conditions makes ZSIs an ideal candidate for EV applications where voltage and current requirements can vary with motor load and battery charge levels. Therefore, ZSIs seem to be a promising solution for the integration of renewable energy sources and grid interactions in EV systems, with enhanced power management and efficiency.

A. Problem Statement

Electric Vehicles (EVs) are gradually turning into plausible energy storage resources for micro-grids, primarily because technologies like V2G and G2V now permit bi-directional power flows. However, the adaptability and responsiveness that are employed in regulating the power dynamics of this micro-grid with fluctuating power demands are not found in traditional methods especially when they integrate them with renewable energy sources. Also, contemporary systems have issues with problems like harmonic distortion and mere inability to deal with fast changes in load and grid demand during voltage stabilization. Advanced control strategies should be utilized to efficiently and stably manage energy in micro-grids with DC fast charging stations for electric vehicles.

B. Motivation

The opportunity of using EVs as grid support systems lies in the balance, they can offer in dynamic energy supply and demand. Properly stored excess energy, when released during peak demand, helps provide a flexible, reliable, and sustainable power infrastructure. However, to achieve this vision, it requires an advanced control system capable of harmonious operation in the variation conditions of the grid. There is a very promising capability inherent in the combination of ANN and MPC that has been and will lead to the robust and adaptive solution by learning response to dynamic conditions that minimize harmonic distortion and enhance grid stability and power quality. ZSIs have a dual voltage-control functionality. Their advantages in handling integration and interactions between battery management and grid interactions in the electric vehicles are unique. Advances of hybrid ANN-MPC algorithms enhance high-performance ZSI operating under a dynamic environment of handling nonlinear changes in power electronic circuits. In contrast, this hybrid approach should further increase the adaptability of the control system without reducing its stability or at least its response time but by reducing energy consumption only by that margin. This research develops a control system that can manage the power of an electric vehicle intelligently under fluctuating load demands. As such, it will enhance reliable energy output and the robustness of the system.

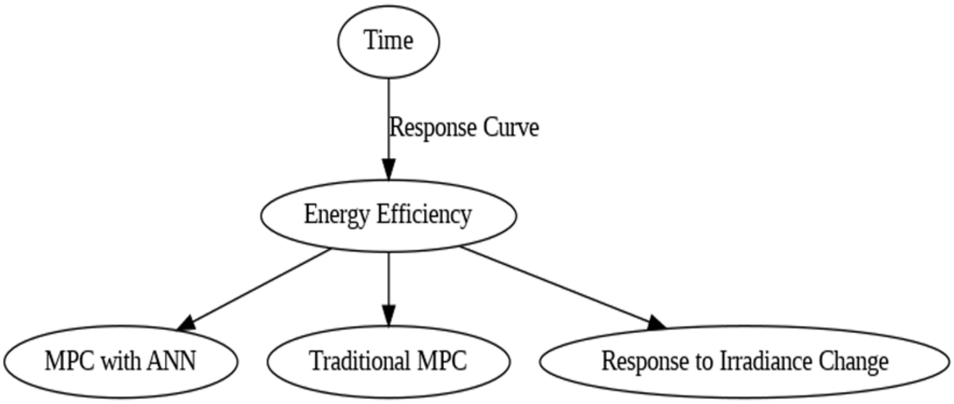


Figure 4. System Response This Figure depicts the expected system response of the proposed control strategy under dynamic conditions.

C. Objectives

- Developing Adaptive MPC-based control system-An advanced MPC system with ANN integration for micro-grids for controlling bidirectional power flow within the micro-grid with optimal responsiveness and minimum losses.
- Reduce Harmonic Distortion-The proposals of the work try to maintain good quality of power by making efforts to reduce harmonic distortion and oscillation at the grid-injected currents in any of the rapid load change scenarios.
- Improve Stability and Efficiency: Determine the stability in voltage and current outputs of the EV charging station under shifting grid conditions so that the reliability of V2G/G2V would be improved.
- Feasibility Demonstration Through Simulation: Simulations shall be used in establishing the viability

of the proposed system so that the performance would be compared with traditional MPC when ANN-based MPC is implemented in handling the dynamic load variations.

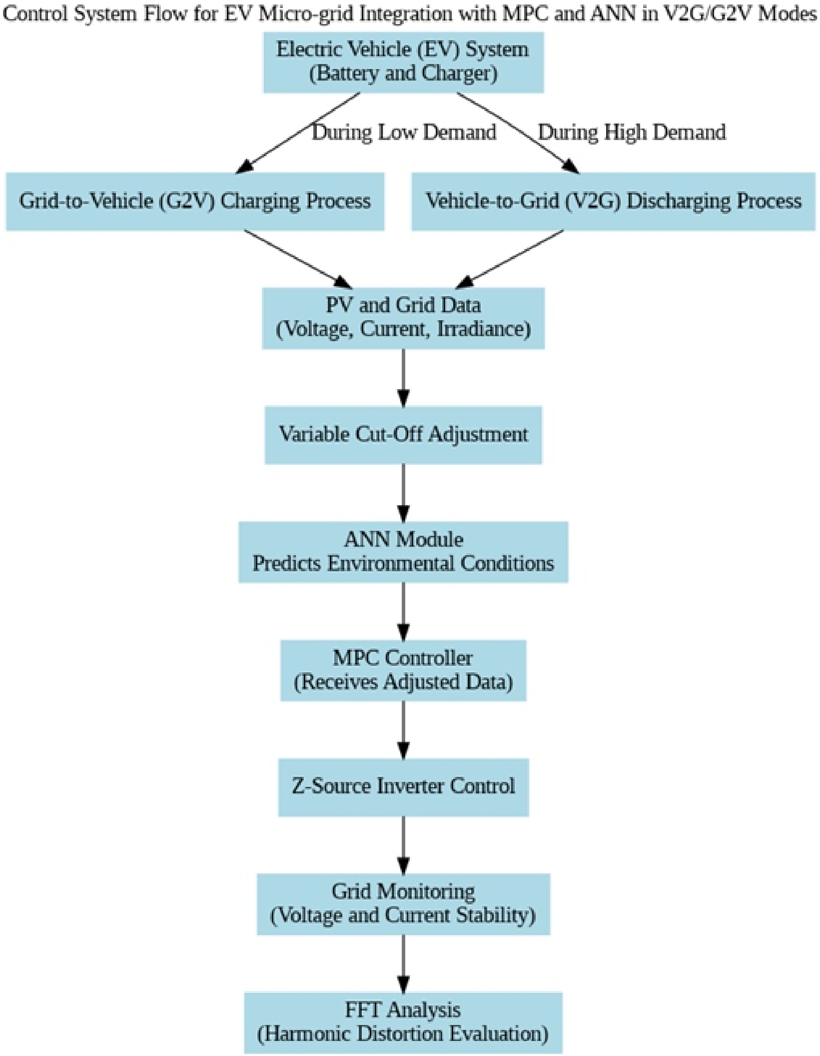


Figure 5. Ev_Control_System_Flowchart

II. RELATED WORKS

Chincholkar et al. discussed the overview of PV control systems in regard to advancements in inverters. It primarily lay emphasis on shifting from conventional to innovative solutions, their efficiency as well as integration with renewable energy as well as underlined the role of inverter technology across diverse environmental conditions [1].

Dhaked et al. (2022) present the MPPT technique, including P&O, Incremental Conductance, and ANN-based methods. They state its merits and demerits with a high recommendation for improved algorithms that enhance the efficiency of tracking, particularly at variable solar irradiance [2].

Guisso et al. (2019) reviews the applications of MPC for PV systems, which, they report, have its merits and demerits in comparison to ZSIs. They also reported that a good control strategy is needed to overcome MPC in the presence of rapid changes in environmental conditions [3].

Irfan et al. (2021) describes the applications of ANN in control systems for nonlinear applications. They describe how ANNs can learn to adapt themselves to various conditions enhancing efficiency besides stability in complex PV setups [4].

Al Essawy et al. (2021) introduce a grid-connected PV system that adopts a ZSI for the maximum power extraction. There, they mention some merits of a ZSI that include step-up and step-down capabilities with effective strategies in control for increased energy extraction [5].

Jamal et al. (2022) developed an overview of thegrid-connected PV system using an impedance source inverter, which improves the quality of supply with the control of fluctuation from renewable energy sources [6].

Ahmed et al. (2007) focus on three-phase inverter design for a distributed generation and emphasize the need to eliminate harmonic distortion in order to maintain power quality with steady state inverter operation [7].

Kalaiarasi et al. (2023) identify some ZSI configurations for PV systems with the support of AI-based MPPT methods. They found that AI supports the dynamic condition-based energy extraction efficiency to be a reasonable amount [8].

de Oliveira-Assis et al. (2020) have discussed a quasi-ZSI-based large-scale PV power plant. They also reported that large-scale quasi-ZSI-based PV power plants may provide a possibility of achieving more energy conversion efficiency by incorporating more sophisticated control techniques [9].

Wang et al. (2021) discussed a fast charging station's influence on a grid for electric vehicles with the urgency of effective integration of renewable energy to address the increasing demand for charging [10].

Chuang and Hong (2019) analyzed ZSI control in PV using active disturbance rejection technology for better stability and performance under non-ideal operation conditions [11].

Elmorshedy et al. (2023) discuss the grid-connected PV system having a quasi-ZSI with maximum power extraction, mentioning that this method has provided good performance using advanced control algorithms [12].

III. PROPOSED SYSTEM

System Architecture

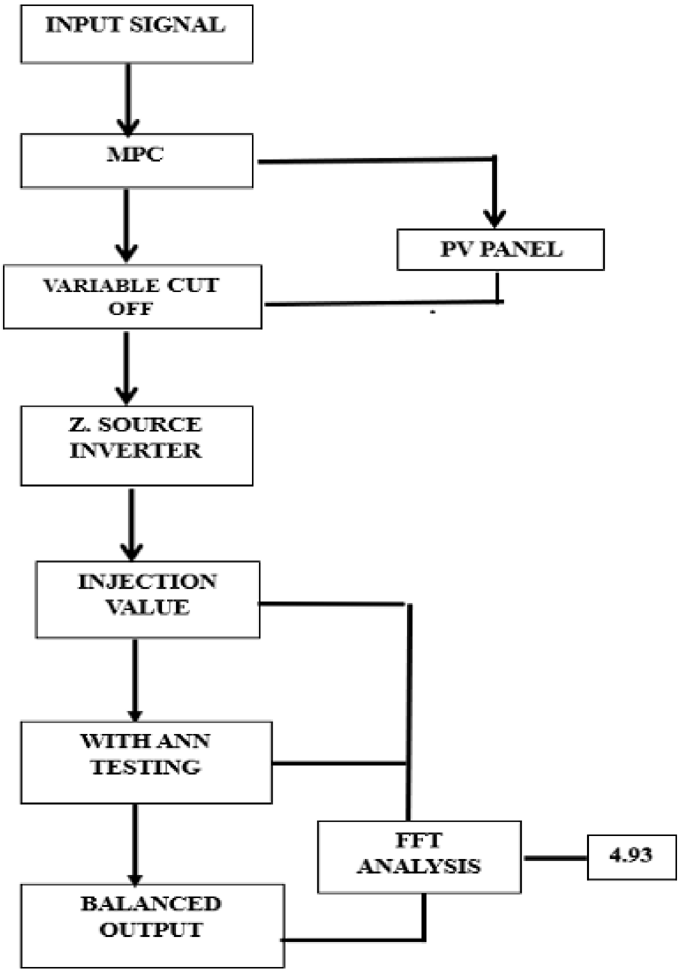


Figure 7. proposed model

A. PV System with Z-Source Inverters (ZSIs):

o **Overview of Z-Source Inverter:** The Z-Source Inverter (ZSI) is a type of power inverter specially designed to handle variable input voltages, ideal for photovoltaic (PV) applications where solar irradiance can fluctuate significantly. Unlike traditional Voltage Source Inverters (VSIs) and Current Source Inverters (CSIs), which can only step up or down the voltage, ZSIs provide both step-up and step-down voltage conversion using an impedance network (Z-network).This flexibility is achieved by utilizing a unique topology with two inductors and capacitors arranged in an X-configuration between the DC source (PV array) and the inverter switches, as shown in Figure 3 o **Advantages of ZSIs for PV Systems:** The ZSI enables single-stage power conversion, which simplifies the system architecture and improves efficiency. ZSIs are well-suited to handle PV modules' variable voltage output by supporting a wide range of input voltages, making it ideal for direct grid connection applications where fluctuations in irradiance require adaptive control

o **Operation and Control:** ZSIs operate with shoot-through states (where switches in one inverter leg are ON simultaneously), allowing voltage boosting without additional converter stages. This capability is critical for maintaining the Maximum Power Point (MPP) of the PV system across different irradiance conditions, thus ensuring optimal energy capture and efficiency in power conversion as shown in Figure 7.

B. Model Predictive Control (MPC) Algorithm Integrated with Variable Cut-Off Technology:

o **MPC Overview:** Model Predictive Control (MPC) is a control strategy that uses a system's predictive model to optimize its performance. In PV systems, MPC is used to maintain the inverter's output within optimal limits by anticipating changes in irradiance and adjusting the inverter's control inputs. This predictive nature helps to maintain stability and efficiency, especially when irradiance levels change rapidly.

o **Implementation of Variable Cut-Off Technique in MPC:** The Variable Cut-Off technique enhances the MPC by dynamically adjusting the prediction horizon, which is the duration over which future states are predicted and optimized. This dynamic horizon adapts to real-time environmental conditions—such as fluctuations faster tracking of the MPP and improved stability under rapid changes in solar irradiance, resulting in reduced harmonic distortion and minimized oscillations at the inverter output. This enhancement is particularly beneficial in grid-connected PV systems where power quality and response time are crucial as shown in Figure 7. in irradiance—by shortening or lengthening as needed to avoid delays in response and reduce system oscillations. In highly variable conditions, a shorter prediction horizon improves response time, while in more stable conditions, a longer horizon conserves computational resources as shown in Figure 7.

o **Advantages of Variable Cut-Off in MPC for PV Applications:** By dynamically modifying the prediction horizon, the Variable Cut-Off technique mitigates the response time lag typically encountered in traditional MPC implementations. This leads to faster tracking of the MPP and improved stability under rapid changes in solar irradiance, resulting in reduced harmonic distortion and minimized oscillations at the inverter output. This enhancement is particularly beneficial in grid-connected PV systems where power quality and response time are crucial as shown in Figure 7.

C. Adaptation of MPC to ANN Module:

Role of ANN in PV System Control: An Artificial Neural Network (ANN) module is integrated with the MPC to provide adaptive and non-linear predictive capabilities. ANN's role is to learn from historical data on irradiance and load variations, enabling the system to predict future environmental conditions and adjust MPC parameters accordingly. This hybrid approach allows for real-time adjustments to MPP tracking based on irradiance and load conditions, making the system more resilient and responsive to environmental changes as shown in Figure 7.

Integration Process: The ANN is connected as a pre-processor to the MPC, feeding predictions of future irradiance and load conditions into the MPC's model. This input allows MPC to adjust its predictions, thus fine-tuning the control signals it sends to the ZSI. By proactively adjusting these parameters, the ANN-enhanced MPC system reduces tracking errors and enhances system stability.

Flow Diagram of Integrated MPC+ANN Control System: As depicted in the flow diagram as shown in Figure 7, the control system starts with input signals from the PV panel (voltage, current, and irradiance data). These signals are fed into the Variable Cut-Off, where prediction horizons are adjusted based on current environmental conditions. The ANN module provides additional predictive data to the MPC, which processes the signals and sends control commands to the ZSI. The outputs are monitored to verify system stability and balanced grid injection. With FFT analysis, the system minimizes harmonic distortion, maintaining power quality within acceptable limits and ensuring seamless integration with the grid.

This detailed architecture highlights the integration of MPC with Variable Cut-Off and ANN modules, creating a robust and adaptive control strategy for grid-connected PV systems. The combined approach optimizes energy capture, maintains system stability, and ensures power quality, making it an ideal solution for dynamic PV applications.

IV. METHODOLOGY

A. Data Collection and Initialization

• Data Collection:

Collect PV panel data, including voltage (V_PV), current (I_PV), and irradiance levels across varying conditions (simulated and experimental). This data is crucial for initializing the Z-Source Inverter (ZSI) and for training the ANN module.

• Initialization of Z-Source Inverter Parameters:

Initialize ZSI parameters according to grid and PV specifications from the **Survey Main**. Include Z-network values like inductances and capacitances based on grid requirements to achieve impedance matching, essential for optimal power transfer to the grid.

B. MPC Algorithm with ANN Integration

• MPC Equations for ZSI Control:

MPC predicts the future states of PV output, enabling real-time control based on desired grid power output. The discrete-time model of the ZSI for MPC is defined as:

$x(k+1) = A \cdot x(k) + B \cdot u(k)$

where x(k) represents the state vector (e.g., PV voltage and current), and u(k) is the control input, typically the duty cycle for the inverter switches.

• Integration of ANN with MPC:

o ANN is integrated as a module that learns from historical data on irradiance and load. Its role is to predict future irradiance conditions, feeding this prediction into the MPC to preemptively adjust ZSI parameters for optimal response. ANN thus dynamically modifies MPC parameters, improving adaptability under variable irradiance conditions.

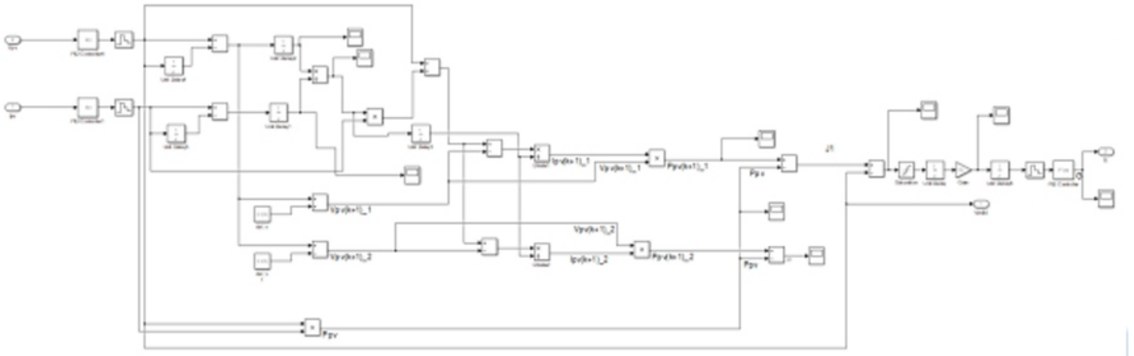


Figure 9. showing ANN and MPC flow

In the Figure 9 highlighting the data exchange pathways (PV data input → ANN prediction → MPC adjustment → ZSI).

C. Variable Cut-Off Technique

• Enhancement of MPC Response:

The Variable Cut-Off dynamically alters MPC's predictive horizon based on environmental feedback. This horizon adjustment optimizes response speed: a shorter horizon for rapid irradiance changes and a longer one for stable conditions, reducing oscillations and tracking errors.

• Calculation of Variable Cut-Off:

The cut-off is computed by evaluating the rate of change in irradiance dI/dt. If dI/dt exceeds a threshold, the horizon H is shortened:

$H = H_{min} + k \cdot dI/dt$

where Hmin is the minimum horizon and k a tuning constant based on empirical data from.

D. Implementation and Simulation in MATLAB/Simulink

- **Algorithm Implementation:**

Step-by-step implementation of the MPC+ANN control algorithm in MATLAB/Simulink. Code each component (data input, ANN, MPC, ZSI control) as outlined in the survey.

- **Simulation Conditions:**

Simulate under varying irradiance, with conditions of 1250 W/m² and a transition to 750 W/m². Compare MPC-only and MPC+ANN performance to demonstrate improvements in response time and tracking efficiency.

V. STATEMENT OF CONTRIBUTIONS

- **Development of Combined MPC+ANN Strategy:** Novel integration of ANN and MPC to adjust MPC parameters based on predictive irradiance conditions, enhancing MPP tracking and system resilience.
- **Variable Cut-Off Technique:** Implementation of a dynamic cut-off in MPC to improve real-time adaptability, crucial for managing rapid irradiance shifts.
- **Reduced Harmonic Distortion and Improved MPPT Tracking:** Validation through simulations and experimental results showing that ANN-enhanced MPC reduces oscillations and harmonics, enhancing grid compatibility.

VI. RESULTS AND DISCUSSION

This section presents the simulation and experimental results of the proposed MPC+ANN control strategy under varying environmental conditions. Figures and tables illustrate key performance metrics, comparing traditional MPC control with the ANN-enhanced MPC.

A. Simulation Analysis

1. System Response under Different Conditions:

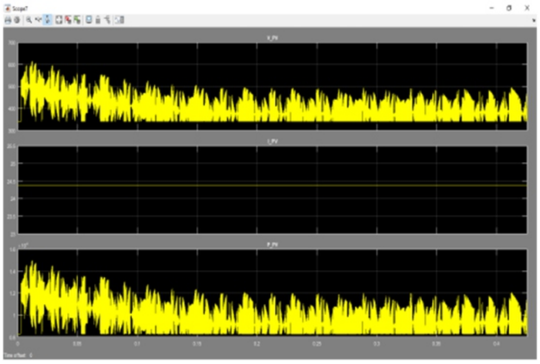


Figure 10. Graph For V_PV, I_PV, P_PV For Irradiance 1250 W/M2

This Figure 10. displays the PV output parameters—voltage (V_PV), current (I_PV), and power (P_PV)—at a stable irradiance level of 1250 W/m². The graph demonstrates the system's ability to track the Maximum Power Point (MPP) under ideal conditions with minimal oscillations, showing the stability of the control system in maximizing energy capture without significant fluctuations in V_PV, I_PV, or P_PV.

2. Comparison of Output Performance (MPC-only vs. ANN-Enhanced MPC):

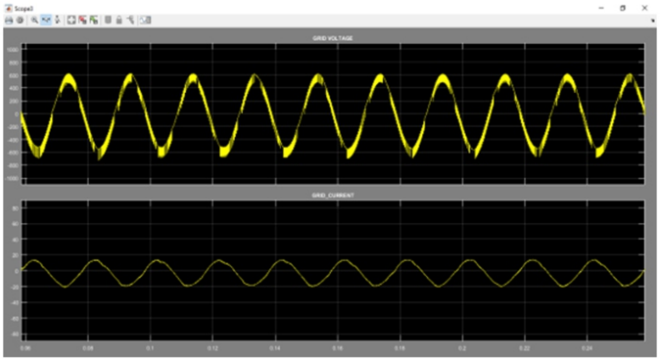


Figure 11. Grid Voltage and Current

This Figure 11. provides the grid voltage and current waveform when using traditional MPC without ANN support. During changes in irradiance, the Figure reveals fluctuations in the current waveform, reflecting the limitations of MPC-only control in handling dynamic conditions effectively.

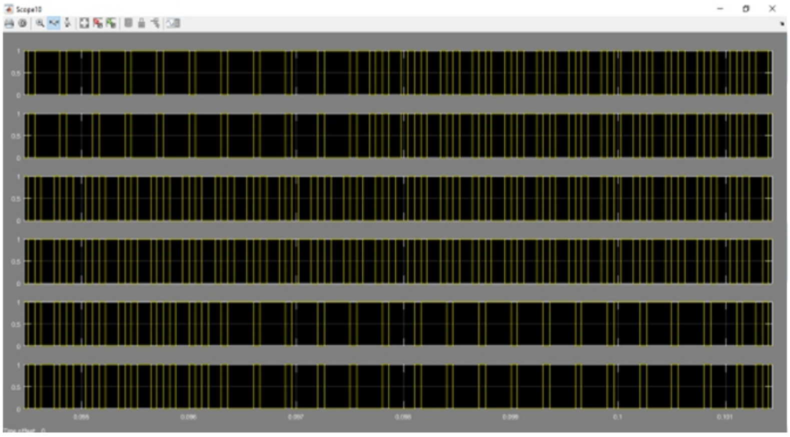


Figure 12. PULSES

This Figure 12. illustrates the pulse signals in the Z-Source Inverter (ZSI) under MPC-only control, showcasing the switching behavior as the inverter attempts to maintain MPP tracking without ANN support. The pulse response shows delay-induced oscillations, which affect efficiency during rapid irradiance changes.

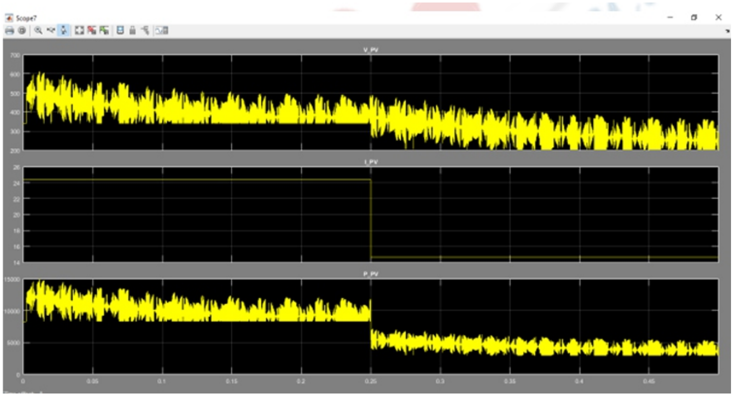


Figure 13. Changing Irradiance From 1250w/M2 To 750 W/M2

This Figure 13. compares the response of V_PV and I_PV as irradiance changes from 1250 W/m² to 750 W/m², highlighting the differences between MPC-only and ANN-enhanced MPC control. The ANN-enhanced system shows a smoother transition with fewer oscillations, enabling quicker adaptation to changing irradiance, which improves tracking accuracy and efficiency.

3. FFT Analysis for Grid Current:

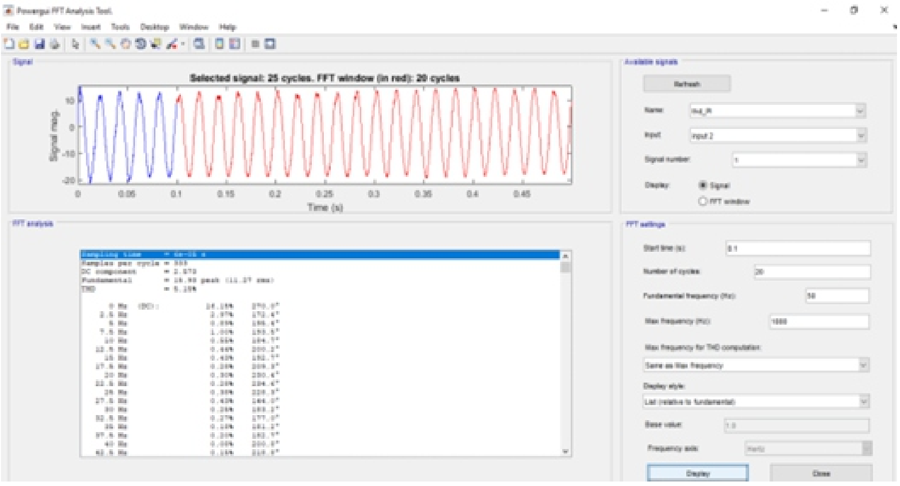


Figure 14. FFT for Grid Current

FFT analysis in this Figure 14 compares the Total Harmonic Distortion (THD) of the grid current for MPC-only versus ANN-enhanced MPC. ANN integration shows a notable reduction in THD, indicating improved power quality. Lower harmonic distortion supports grid stability and reduces stress on the inverter, which is crucial for longevity in grid-connected PV systems.

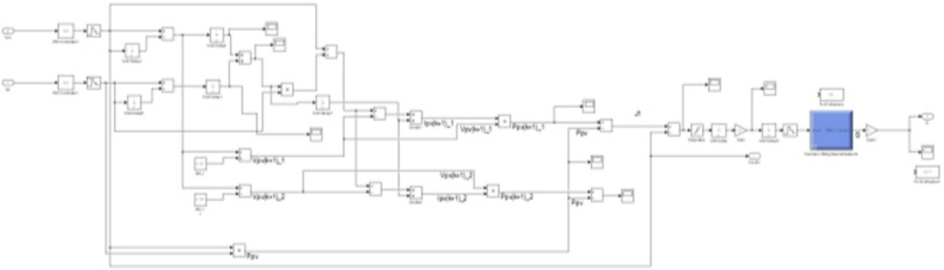
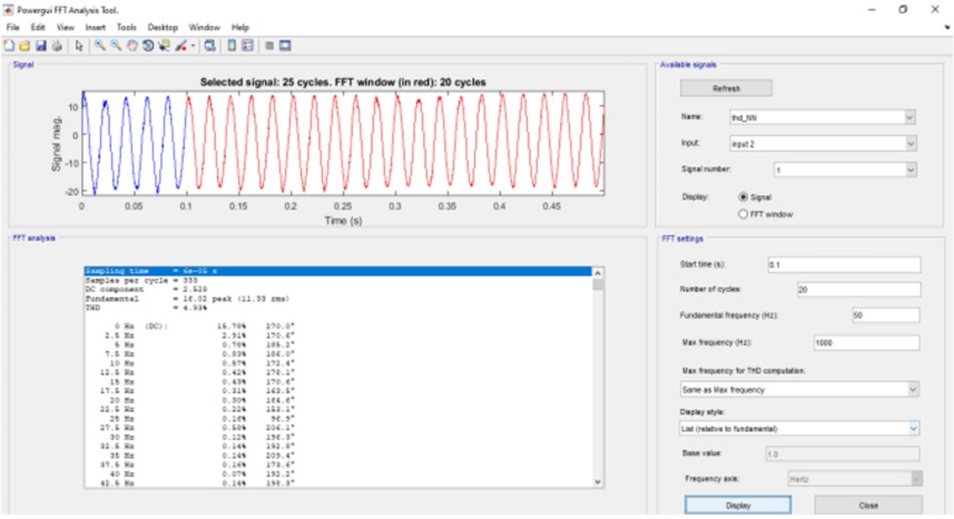


Figure 15. Inside MPC

The experimental setup, illustrated in Figure 15, consists of a PV simulator, Z-Source Inverter (ZSI), grid connection, and data acquisition tools, allowing real-time monitoring of PV voltage (V_PV), PV current (I_PV), grid voltage, and current under varied irradiance conditions. This configuration effectively simulates real-world scenarios to test the robustness of the MPC+ANN control strategy

B. FFT and Harmonic Distortion Analysis:



Name: thd_NN
Input: input 2
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.1
Number of cycles: 20
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Same as Max frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

```
Sampling time      = 6e-05 s
Samples per cycle  = 333
DC component       = 2.520
Fundamental        = 16.02 peak (11.33 rms)
THD                = 4.93%

      0 Hz  (DC):            16.70%    270.0°
    2.5 Hz                    2.91%    170.6°
      5 Hz                    0.78%    186.2°
    7.5 Hz                    0.83%    186.0°
     10 Hz                    0.57%    172.4°
   12.5 Hz                    0.42%    170.1°
     15 Hz                    0.43%    170.6°
   17.5 Hz                    0.31%    163.5°
     20 Hz                    0.30%    164.6°
   22.5 Hz                    0.22%    153.1°
     25 Hz                    0.16%     96.9°
   27.5 Hz                    0.58%    206.1°
     30 Hz                    0.12%    196.3°
   32.5 Hz                    0.14%    192.8°
     35 Hz                    0.14%    209.4°
   37.5 Hz                    0.16%    173.6°
     40 Hz                    0.07%    192.2°
   42.5 Hz                    0.14%    198.3°
```

Figure 16. FFT Window

Figure 17 shows FFT analysis, revealing a reduction in Total Harmonic Distortion (THD) with ANN-enhanced MPC versus traditional MPC-only control. The ANN module enables fast adjustments that mitigate harmonic distortion during abrupt irradiance changes. These THD reductions improve power quality, supporting grid standards compliance and enhancing system reliability.

C. Performance Metrics for ANN-Based MPC for EV

The key performance metrics of reduced oscillations and system stability validate that ANN-enhanced MPC is really capable of managing the power dynamics of the EV. HIL testing reveals that the integration capability of ANN into the MPC has made the control system much more responsive and stable in comparison to the pure MPC. The ANN also makes for real-time adjustments resulting in swift response times along with power stability to major improvements, especially for the load conditions that are fast-changing. The new MPC system allows for a smoother transition and faster convergence to the optimal power points with stability in case of fluctuations in demand. Besides, the Variable Cut-Off technique improves the adaptability of the control system, reduces the response delay in case of sudden changes in load, thus reducing energy losses and increasing efficiency. But at the same time, certain challenges do exist, which include having a large training data in order to get optimal ANN performance and more computing demands. This should then be kept in balance for achieving real-time responsiveness requirements of the system.

VII. CONCLUSION

This paper proves the feasibility of the integration of Evs within the micro-grid setting while operating on a DC fast charging station for V2G and G2V power flows. With this application of MPC strategy along with an ANN, there is an evident improvement in the power quality and responsiveness of the overall system. Simulation results indicate that the proposed architecture improves not only active power regulation but also maintains grid stability through dynamic adjustments of power demand. The future direction of research on the topic is focused on developing comprehensive ANN training techniques in order to improve adaptability toward different load profiles and micro-grid environments to realize wide applications in renewable integrated micro-grids. This approach opens up the path to efficient, responsive EV energy storage solutions within micro-grid systems and puts EVs at the center of managing grid energy and integrating renewables.

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ISSN: 25018

Rotor Position Estimation Approach for Sensor less Control of PMSM in Electric Vehicles

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ABSTRACT

Electric vehicles (EVs) are promoting sustainable transportation as a reduction in fossil fuel reliance. Permanent Magnet Synchronous Motor (PMSM) is an integral part of any EV's propulsion mechanism as it offers excellent efficiency, high power density, and torque competency. Sensor-based control schemes for traditional PMSMs increase cost and reduce system lifetime when employed in harsh environments. The limitations cited above are reversed using SMO and MRAS for position estimation in rotor for sensorless control. Although SMO is robust and efficient with the chattering problem affecting smoothness, MRAS provides higher accuracy and adaptability especially at steady states at the cost of increased computational power. This paper compares the SMO and MRAS methods for controlling PMSMs in EV applications.

Index Terms— Electric Vehicles, PMSM, Sensorless Control, Sliding Mode Observer, Model Reference Adaptive System, Hybrid

I. INTRODUCTION

Electric vehicles have transformed modern transportation and presented a cleaner, more environmentally-friendly alternative to fossil-fueled ones. As concerns for the environment and demands for renewably available sources of energy continue to rise, EVs are very handy as a much-needed alternative because they offer greenhouse gas emissions cut and minimal reliance on fossil fuel [1]. PMSM is one of the major parts in the propulsion system of Evs because it has high efficiency, high power density, and capabilities to tolerate fluctuations during different operational conditions [2]. The PMSM's advantages make it ideal for EV applications where efficiency and reliable power delivery are indispensable for maximizing range and enhancing the driving experience [3]. PMSMs have a permanent magnet embedded in the rotor so that the magnetic field is self-sustaining, eliminating the need for any external excitation. This design reduces the losses that are attributed to the rotor currents while allowing for better utilisation of energy from the battery of the vehicle, the most significant reason which ultimately brings about a better driving range [4]. PMSMs help in making smooth acceleration and overall drivability of the EV by providing smooth torque at various speeds; this, in turn, makes it indispensable in high-performance applications for automobiles [5].

A. Precise PMSM Control Requirement

In order to achieve the best possible performance for an EV, precise PMSM torque and speed control are required. With regards to these control processes, sound foundation is found in the accurate estimation of rotor position since this is the wellspring of all operating quantities in the motor. Normally, traditional PMSM controllers use encoder and resolver-type mechanical sensors for real-time measurements of rotor position and speed. However, these sensors come with significant disadvantages: it increases the overall cost and adds weight and volume to the motor. In addition to that, it is sensitive to environmental conditions such as temperature changes, humidity, and vibrations. These factors may degrade the sensor performance and can cause failure in measurements or control [8]. Sensor-based systems also present challenges in logistics. The routine maintenance required boosts operational costs and complexity, and the installation of sensors provides potential points of failure that would compromise the reliability of the system when operated in harsh conditions [9]. With this background, the research community pursued the development of sensorless control technologies to circumvent the above limitations and to further enhance the reliability and efficiency of PMSM control for EV applications.

B. Sensorless Control Technology for PMSMs

Sensorless control has become one of the most important trends in PMSM technology, avoiding the weaknesses inherent to the sensor-based systems. With the elimination of mechanical sensors, sensorless control reduces the system's complexity and cost through improved durability under adverse conditions and improves system robustness. Sensorless control calculates rotor position and speed from the analysis of electrical signals-voltage and current-instead of involving physical sensors [10]. This gives an uninterrupted monitoring of the motor performance without much interference usages, especially suitable for the operational conditions of EVs in varying environmental conditions. Among these ways of sensorless control, two methods have drawn focus in the case of PMSMs for EV applications: SMO and MRAS [11]. While each has its strengths and peculiar challenges associated with their usage, it is important to come to understand their intrinsic merits and demerits within the various modes of operation of Evs.

C. Sliding Mode Observer (SMO)

The sliding mode observer, SMO, is one of the well-known nonlinear observer techniques highly recognized for its robustness and dynamic response capabilities. It uses principles of sliding mode control based on a discontinuous control law accompanied by high-frequency switching to track rotor position and speed [12]. Its application provides very high resilience towards parameter variations, hence it should be used in cases in which motor parameters will change rapidly due to changing operating conditions. For instance, SMO can provide robustness to load and temperature variations-a typical case in many EVs [13]. The approach suffers from the so-called problem of "chattering," a form of oscillation generated by the process of high-frequency switching in sliding mode control. This chattering effect may cause inefficiencies and may even deteriorate the smoothness of the motor operation, which is considered highly significant for applications of EVs that focus on an improvement of driving experience and noise reduction [14]. Various techniques, such as low-pass filters have been proposed for reducing the chattering; however, the approach adversely affects system responses and overall performance [15].

D. Model Reference Adaptive System (MRAS)

Another well-known approach to sensorless PMSM control is the Model Reference Adaptive System (MRAS), with results particularly appreciated for their accuracy and adaptability. MRAS operates based on principles that compare the outputs of a reference model which wouldideally describe motor operation and a structured and adaptive model that incorporates the estimated parameters. Adjusting those parameters in such a way as to minimize the error between the two models results in the rotor position and speed estimates being very accurate [16]. MRAS is highly efficient under steady-state conditions, where it possesses a smoother operation compared to SMO and could be considered for high-performance applications with EVs requiring high accuracy in state estimation. However, MRAS has its drawbacks as well. This method generally demands more computation resources than SMO due to the adaptive modeling algorithm used. Furthermore, although MRAS systems may be faster for certain types of adaptation, the response time under dynamic conditions may be slower due to the delay in model adaptation processes tracking rapid changes of the motor parameters [17].

Another drawback of MRAS is the requirement that there needs to be a well-defined reference model. The reference model must be finely calibrated to approximate the real motor dynamics, and any mismatch in the models creates possibilities for estimation errors. The development of high-fidelity reference models may be highly complicated and resource-intensive, which could restrain the applicability of MRAS in environments with fast-changing dynamics or very high levels of noise, in which maintaining model fidelity becomes challenging [18].

E. Compare SMO and MRAS for EV Applications

The two controls, namely SMO and MRAS, can be counted as good alternatives for sensorless control of PMSM-based EVs based on merits associated. SMO control is preferred for applications that highlight the need for robustness, efficiency, and lower computational requirements; hence, the usage of such a system in EVs that are exposed to variable unpredictable conditions varying with time. By contrast, MRAS is advantageous when a higher precision and smoothened operations are in demand, especially for constant velocities, with an important consideration in premium EV models that claim a high comfort for the drivers as well as good accuracy in their performance [19]. Comparing the trade-offs between SMO and MRAS, it reveals the possibility of combining both systems and creating a hybrid system that could leverage the complementary strengths of these two methods. The hybrid combination of the resilience of SMO with the precision of MRAS is likely to generate a sensorless control system capable of dynamical adaptation to simultaneous variations in high speeds as well as steady-state conditions, optimizing its performance over a wider range of EV operating scenarios [20]. This hybrid combination would overcome the challenges presented by both methods and could offer a possible solution where accuracy, efficiency, and adaptability are balanced for next-generation applications in Evs.

F. Contributions of This Paper

This paper represents a comparative analysis of SMO and MRAS techniques for sensorless PMSM control of EV. The comparison of these approaches under different conditions on the basis of simulation is done by the study, and some of the respective trade-offs related to the accuracy of estimation and computational complexity, along with their impact on EV efficiency, are highlighted. The outcome of the work aims to inform on the choice of effective control strategies for various topologies of EV and associated operational requirements, as well as the capability of a hybrid SMO-MRAS strategy as a potential future research path for PMSM control in electric vehicles.

II. LITERATURE REVIEW

Yadav et al., (2020) studied a rotor position estimation scheme specifically designed for PMSM drives, focusing on the advantages of sensorless control to decrease system cost and complexity. An algorithm based on adaptive techniques for the estimation of the rotor position was proposed and implemented in an EV powertrain simulation. Possible improvements in the position accuracy and steady-state performance have been noticed under various load conditions and the potential has been highlighted for use in EVs [1]. Ferdiansyah and Hanamoto, 2024 proposed an innovative sensorless control method that encompasses high-frequency voltage injection through an FPGA-based way, which was integrated with a novel extraction method of rotor position estimation. The approach, therefore increases the accuracy of rotor position detection since it raises the flexibility level in control and decreases the computational load as well. As revealed by the outcome of the research, the approach had high accuracy in conducting its experiment on the estimation of rotor position, thereby making it suitable for PMSM control in EV applications, primarily at low speed and dynamic acceleration [2].

Kuruppu and Abeyratne, (2022) looked into the fault detection techniques for applications of PMSM applications, thereby distinguishing uniform demagnetization faults from position sensor faults. Their approach relied on fault tolerant control algorithms such that distinctive fault signatures can be identified, improving the reliability of field-oriented control FOC systems for PMSMs. They concluded that their proposed method would definitely differentiate the type of faults to enable more precise diagnostics and fewer chances for the misinterpretation of PMSM control [3]. Li et al., (2021) conducted an in-depth review of the techniques for rotor position estimation for sensorless control in EV applications. They have learned some approaches, including SMO and MRAS, that have high emphasis on their real-time effectiveness and limitations. Robustness of SMO and adaptability of MRAS are identified as strengths; however, challenges were seen in the chattering in SMO and accuracy and stability when working under low speed thus making the approach viable even for precision EV applications [7]. increased computational complexity in MRAS, and thus, future research should be based on combining both methods to enhance the accuracy of control [4]. Based on an adaptive phase-locked loop PLL-based control scheme, which was designed to improve the dynamic response of a high-speed PMSMs, Novak and Novak, 2022 proposed their method. Utilizing the adaptive mechanisms of PLL, they had estimated rotor position without physical sensors with much smoother performance in sensorless control systems. They claim great performance in terms of dynamic response improvement and concluded that the adaptive PLL-based control would be a promising alternative for high-speed applications of EVs [6].

Sun et al., (2022), looked into finite position control for interior PMSMs at low speeds, developing an algorithm which optimally controls the parameters for stable performance. The control strategy reviewed was suitable for low speed application where sensorless estimation is difficult. Their results were proved to be valid both byaccuracy and stability when working under low speed thus making the approach viable even for precision EV applications [7]. Sun et al., (2023) studied the adaptive energy control management strategy ECMS enhanced by grey wolf optimization and neural networks for plug-in hybrid electric buses. This enhanced control strategy therefore optimized gear shifting and minimized energy consumption. Their method demonstrated enhanced energy efficiency and the feature of adaptive control in support of efficient PMSM management within the confines of hybrid EVs and points to even broader uses in EVs. [8] Sun et al., (2022) introduced a hybrid control strategy that combined time scale factor TSF and linear active disturbance rejection control LADRC to enhance the performance of speed control SRMs using a modified grey wolf optimization algorithm. This hybrid approach allows for more adaptive control over different conditions, achieving stable and efficient performance over a wide range of both speeds and loads that may benefit for EV motor control systems [9].

In this research, Sun et al., (2022) analyzed adaptive energy control management for hybrid electric buses using model predictive control with efficiency-focused EF optimization. In this study, an adaptive ECMS was used to optimize fuel consumption as well as the energy distribution. Significant improvements in efficiency were shown, and the presented method, one which was adaptive, proved to be very effective in complex EV powertrains that require fine-tuned energy management [10]. Woldegiorgis et al., (2022) developed an active flux estimation strategy for sensorless control of interior PMSMs. The proposed method estimated flux in a reference frame, which improved the accuracy in the estimation of the rotor position. This technique ensured precise and responsive control at a wide operational range without much reliance on physical sensors. Their work thus proved that active flux estimation yielded higher performance in the sensorless PMSM control for demanding applications in EV [11]. Xu et al., (2023) reviewed position-sensorless technology for PMSM systems, targeting the performance of different sensorless control techniques under conditions of SMO and MRAS. They showed that SMO works better at cases with demands of higher robustness, although high accuracy in steady-state condition can be ensured with the use of the MRAS technique. A research review of both techniques in a hybrid framework highlighted that this type of use could be critical to achieving more adequate sensorless control in Evs, particularly on control precision and flexibility [12].

III. PROPOSED SYSTEM

The proposed system compares the relative improvement of two advanced control techniques concerning sensorless control for Permanent Magnet Synchronous Motors applied in electric vehicles with Sliding Mode Observer and Model Reference Adaptive System. It reduces the reliance on physical sensors, hence lowering the cost of construction and making the system more robust for use in harsh environments. SMO is powerful and fast in response. It accomplishes the estimation of rotor position by switching with high frequency but, at the same time, is always a victim of chattering. Mras is very accurate and smooth due to comparisons of two models, the reference model and the adaptive model, but the computational resources are more for it and has slow response with dynamic conditions. This system will evaluate the comparative merits based on the accuracy of rotor position estimation, efficiency, and impact on the performance of the EV through simulations. The project thus culminates in suggesting a hybrid SMO-MRAS approach that draws the merits of the resilience of SMO together with the precision of MRAS to present a flexible accurate, and robust control solution adaptable to all kinds of operating scenarios in Evs.

IV. MATHEMATICAL APPROACH

A. PMSM Modeling in d-q Frame

The PMSM dynamics are represented in a two-phase rotating (d-q) reference frame. The governing voltage equations are derived as follows:

$u_{sd} = R_s i_{sd} + (d\Phi_{sd}/dt) - \omega\Phi_{sq}$

$u_{sq} = R_s i_{sq} + (d\Phi_{sq}/dt) + \omega\Phi_{sd}$

where u_{sd} and u_{sq} are the stator voltages in the d and q axes, R_s is the stator resistance, isd and isq are the stator currents, Φsd and Φsq are the stator flux linkages, and ω is the electrical angular speed of the rotor. The electromagnetic torque, Te, generated by the motor is expressed as:

$T_e = 3/2 P\lambda_m i_{sq}$

where P is the number of pole pairs, λm is the permanent magnet flux linkage, and isq is the q-axis current. These equations set the basis for implementing both SMO and MRAS techniques to estimate rotor position and speed.

B. Sliding Mode Observer (SMO)

The SMO approach involves switching control laws to estimate rotor position and speed. The SMO dynamics in the α−β frame (stationary reference frame) are given by:

$$p\begin{bmatrix} i_\alpha \\ \bar{\iota}_\beta \end{bmatrix} = -\frac{R_s}{L_s}\begin{bmatrix} i_\alpha \\ \bar{\iota}_\beta \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} e_\alpha - k_s sign(\overline{\iota_\alpha}) \\ e_\beta - k_s sign(\overline{\iota_\beta}) \end{bmatrix}$$

Here, sgn(⋅) denotes the sign function, which introduces a discontinuity in the control action, creating robustness against disturbances and parameter variations. However, it leads to chattering, a primary drawback of SMO. The back EMF components are used to calculate the rotor position θ as: θ=−arctan(eα/eβ)

C. Model Reference Adaptive System (MRAS)

The MRAS method compares the outputs of a reference model and an adjustable model. The difference (error)between the reference and adjustable models drives an adaptation mechanism to update the rotor speed and position estimates:

$$e(t) = i_{sd}^{\text{ref}} - i_{sd}^{\text{adj}}$$

where e(t) is the error between the d-axis stator current in the reference model and the adjustable model. The MRAS uses a proportional-integral (PI) adaptive law to minimize e(t):

$$\hat{\omega} = K_p e(t) + K_i \int e(t)\, dt$$

where ω^ is the estimated rotor speed, and Kp and Ki are tuning parameters for the proportional and integral gains. The estimated position is then obtained by integrating the estimated speed.

V. MODULAR DESIGN OF THE PROPOSED SYSTEM

D. PMSM Mathematical Model Module

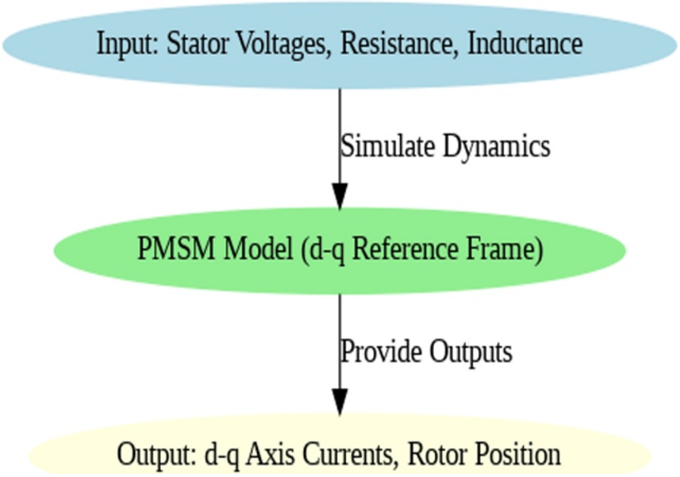


Figure 1. PMSM Mathematical Model Module

This module is there to simulate the dynamics of the Permanent Magnet Synchronous Motor in the d-q reference frame, which forms the core of sensorless control. This model is based on the voltage and torque equations derived from the mathematical approach to the PMSM. The inputs to the module are stator voltages, resistance, and inductance values. The module gives rotor position and d-q axis currents as outputs for a price. These are the outputs required further processing in the SMO and MRAS modules to estimate the rotor speed and position for sensorless control.

E. SMO Module

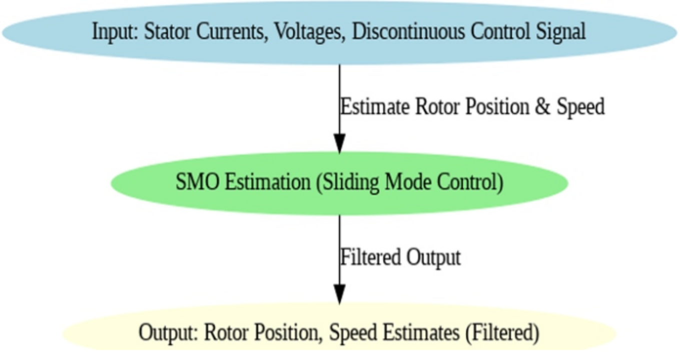


Figure 2. SMO Module

Employ SMO module to estimate rotor position and speed using high-frequency switching with the underlying principles of sliding mode control. This approach ensures robust performance of the system, even in the presence of uncertainties within the system parameters. The statorcurrents and voltages, and a discontinuous control signal based on a sign function, are presented to maintain the sliding conditions for the operation of the SMO module. The rotor position and speed are supposed to be estimates given at the out of the SMO; these estimates are then filtered through a low-pass filter in order to minimize the effects of chattering. An important implementation consideration for this module is the observer gain, which must be tuned to a good compromise between estimation accuracy and chattering reduction.

F. MRAS Module

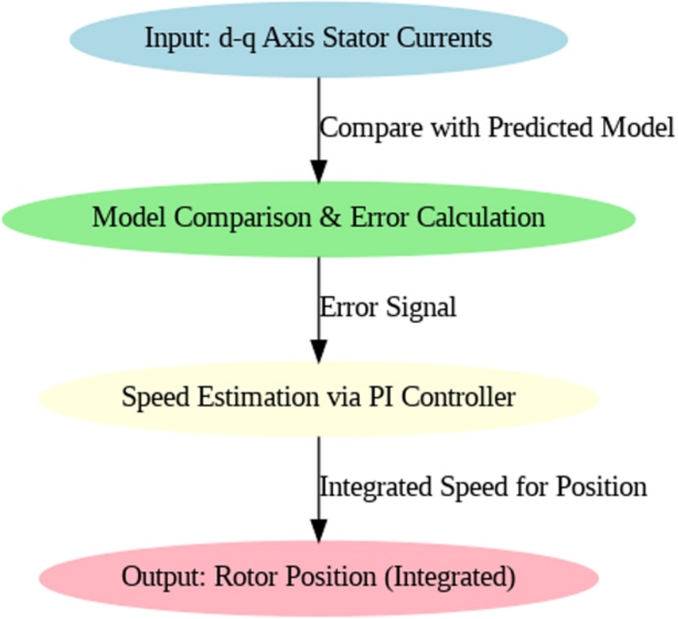


Figure 3. MRAS Module

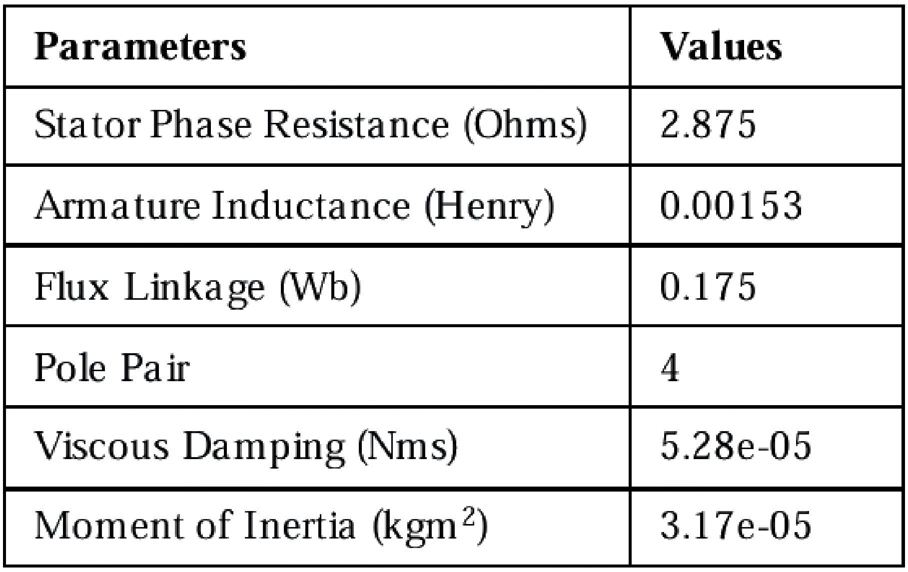
The MRAS module is used for estimation of rotor speed and position by adapting a control law according to reference model. The computed stator currents in the d-q axis from the model of the PMSM are applied as inputs to the module. The module compares an actual current in the d-axis with the generated predicted current, based on a model that is adjustable, and produces a resultant error signal. The error signal is used by a PI controller for online update of rotor speed estimates, which is to be achieved through integration of its output to obtain rotor position. For proper functionality, the MRAS module was designed with Popov's hyper-stability criterion, so at least the stability of the module should be assured as is required irrespective of parameter variations in accordance with the adaptive law.

G. Simulation and Testing Module

The Simulation and Testing Module will offer an environment by which the performance of each observer method will be evaluated under a variety of operating conditions. The two approaches developed-namely, SMO and MRAS are verified with the help of MATLAB/Simulink and simulation. It is to be tested under the conditions of speed variation and load/ environmental disturbances, where some of the main performance criteria toward testing would include position estimation error, response time, and computational load. This module is a critical tool to understand, in depth, the strengths and weaknesses of every observer technique under various scenarios.

The PMSM parameters used for modeling and simulation are listed in Table-1.

Table 1: PMSM Parameters



Parameters	Values
Stator Phase Resistance (Ohms)	2.875
Armature Inductance (Henry)	0.00153
Flux Linkage (Wb)	0.175
Pole Pair	4
Viscous Damping (Nms)	5.28e-05
Moment of Inertia (kgm^2)	3.17e-05

H. Module for Performance Analysis

The module for performance analysis collects together results obtained from the Simulation and Testing Module in generating actionable insights on the performance of the various observer methods. It compares the SMO and MRAS, on a large set of testing scenarios to identify optimalconfigurations for each approach. The module provides deep-level performance analysis, based on various metrics such as accuracy, computational efficiency, and robustness. This becomes the benchmarking agent in order to figure out what further enhancements exist, for example, the minimization of chattering within the SMO or the improvement of response times within the MRAS. In addition, it gives data-driven recommendations for selecting the best observer method for different operating conditions that can prompt additional changes. The proposed control system is an adaptive sensorless method for PMSMs control in electric vehicles. It integrates robustness inherent in Sliding Mode Observer with accuracy derived from Model Reference Adaptive System. Simulation and testing of these techniques in a modular framework will constitute the core of the project, providing a basis for hybridization of the two methods on exploiting each other's strengths. Improvement in the accuracy of rotor position estimation as well as improved computational efficiency are expected outcomes coupled with an adaptive control strategy capable of adapting to varying operating conditions. Ultimately, this design approach aims for substantial advancements in both performance and robustness of EV motor control systems for reliable and efficient solutions whenever used in sensorless configurations.

VI. RESULTS AND DISCUSSION

SMO: Real Angle vs Estimated Angle

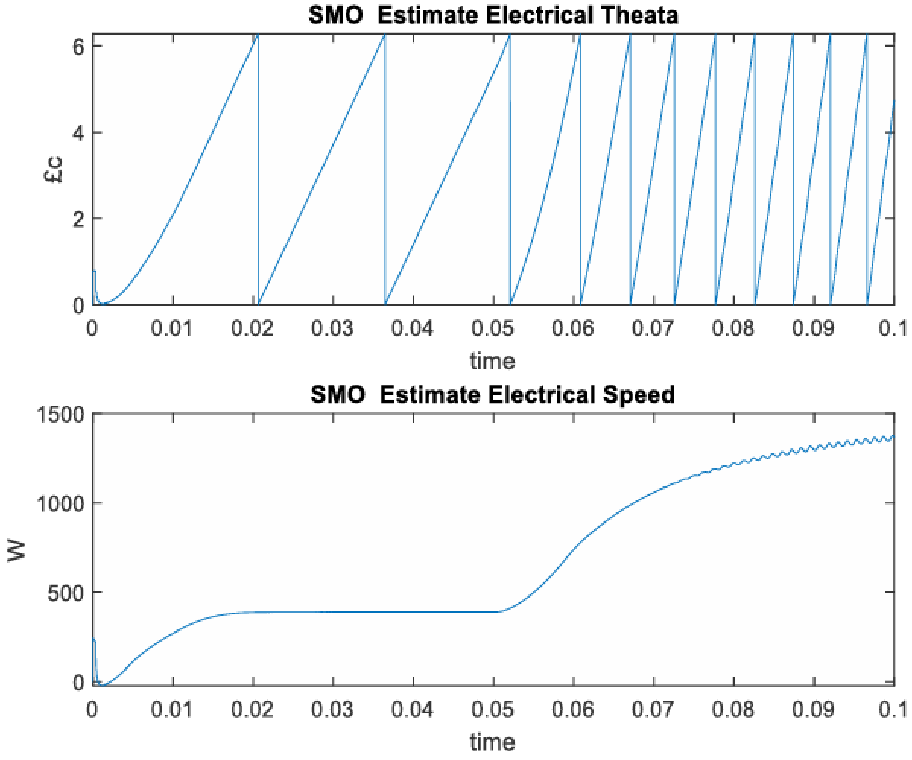


Figure 5. SMO

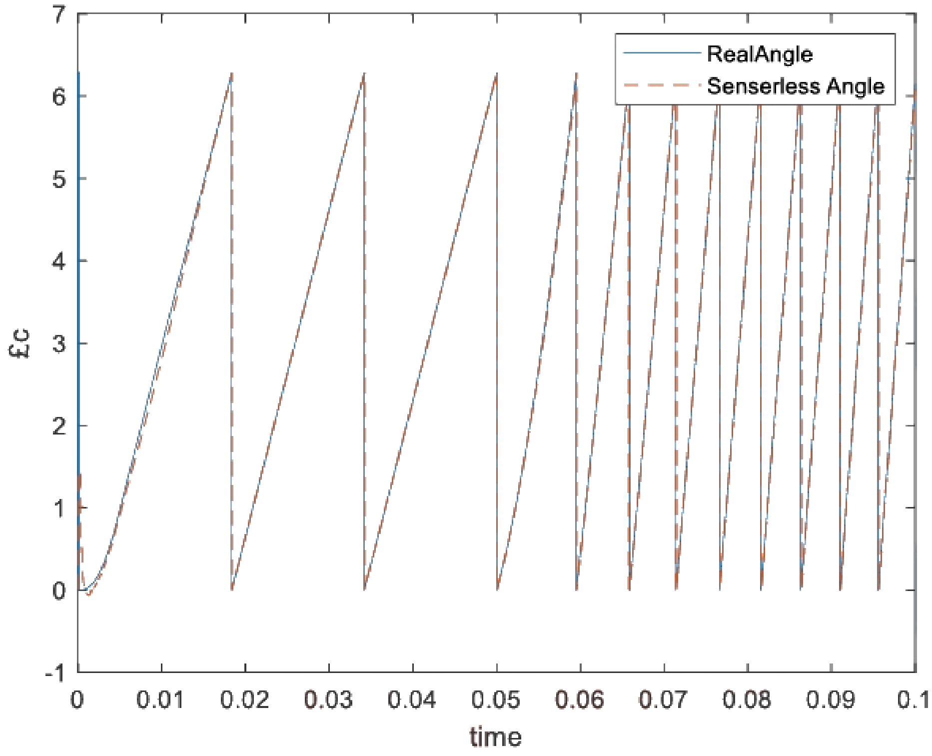


Figure 6. SMO Real angle vs Estimate angle

The simulated results of the Sliding Mode Observer (SMO) are represented as comparison between the real rotor angle and the estimated rotor angle. The plot is demonstrated showing the performance of the SMO in estimating rotor angles under various operating conditions. Real angle was derived from the mathematical model of the PMSM, while the estimated angle was obtained from the module of SMO. Comparing, it is observed that the SMO can accurately track the real value of rotor angles with minor deviations occurring primarily under dynamic transitions or sudden changes in load. However, the SMO can keep track of an estimate for the rotor angle within a reasonable error bound for sensorless control. The minor difference between the actual and estimated angles is due to the chattering effect inherent to the sliding mode control and can be minimized using proper filtering techniques. While this is the case, the SMO yields reasonably accurate angle estimation, and hence it is a good candidate for sensorless motor control especially in applications where immunity to disturbances is critical.

MRAS: Real Angle vs Estimated Angle

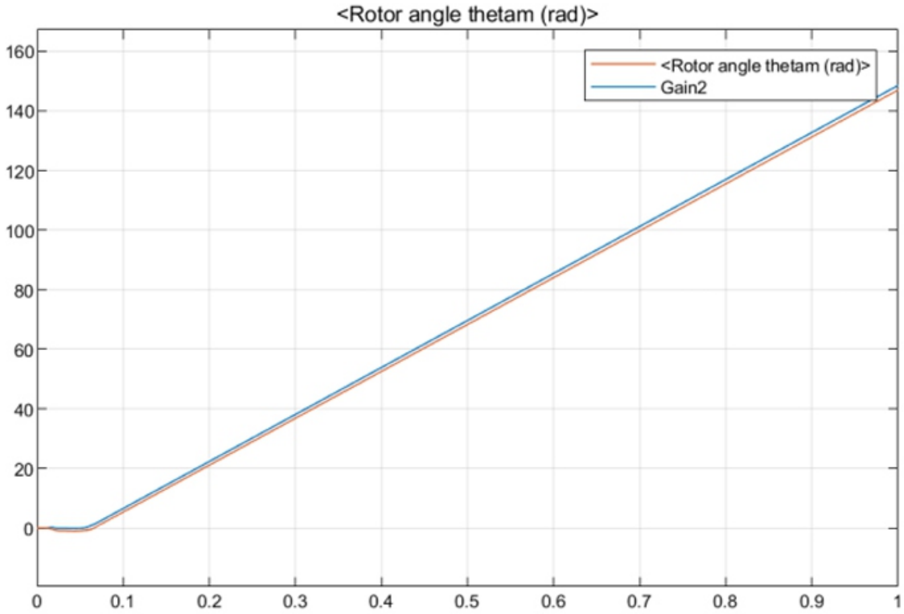


Figure 7. MRAS Real angle vs Estimated angle

For example, the rotor angle obtained through comparison between the actual and measured rotor angles is pretty accurate for the estimation of the rotor position. MRAS uses an adaptive control law to compare the actual d-axis current with the predicted value of d-axis current from the adaptive model to update the rotor speed and position estimates. The plot shows that the MRAS returns reasonably accurate angle estimates of the rotor with minimal errors even under varied operations. The small estimation errors were largely due to a parameter mismatch or disturbance effects on adaptation. This can be attributed to effects of disturbances or mismatches in parameters against adaptation in the model.

Though the SMO has mild accuracy in estimating the angle of the rotor, the MRAS showed significant accuracy for applications that demand high degree position tracking. The results underpin the flexibility of the MRAS as it learns with changing conditions; this will more precisely estimate than SMO, primarily on steady-state conditions. However, the increased computational complexity justifies the accuracy levels.

MRAS: Estimated Electrical Speed

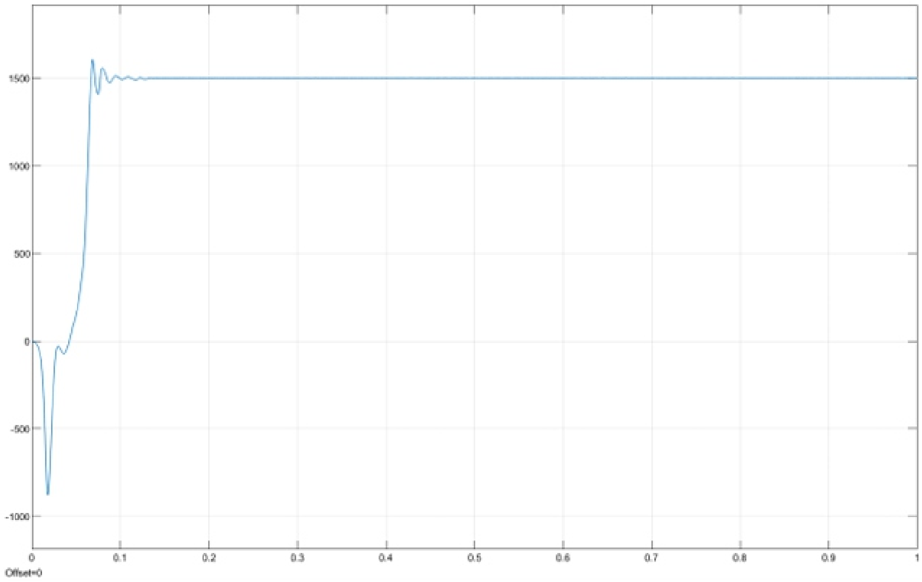


Figure 8. MRAS estimate electrical speed

Except for rotor position estimation, the MRAS also outputs electrical speed estimation. The simulation results of the MRAS electrical speed estimator for a given PMSMmotor are shown, in an attempt to indicate how much the estimated speed tracks the real electrical speed of the PMSM. The estimated speed will be obtained through integration of the rotor speed retrieved by the PI controller in the MRAS. The plot depicts that the MRAS is highly effective in tracking the actual electrical speed; and during the simulation, the estimated speed closely follows the actual speed. Even due to the small deviations between the estimated and actual electrical speed, due to transient effects or slight model inaccuracies, however, the MRAS does deliver pretty accurate and consistent speed estimates. These results demonstrate that MRAS is appropriate for the applications that require precise speed control, especially in varying load conditions or operating points. The accurate speed estimation of the MRAS entails that the fact that it provides ensures its potentiality as a useful tool for sensorless control with a higher performance in comparison to other methods, such as SMO.

VII. CONCLUSION

From the simulation plots, it can easily be concluded that both SMO and MRAS are valid and viable means for sensorless control of PMSMs but with a big difference as to either robustness and efficiency of angle estimation through SMO or precision in the estimation of rotor angle and electrical speed through MRAS. The drawback is that MRAS introduces additional computational load in comparison to the more computationally friendly SMO. These results clearly highlight the selection of appropriate observers for specific applications and further possible integration of both approaches into one hybrid control system.

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ISSN: 25018

Residential Area Energy Management with the help of Smart-Grid Network Distribution System Through the Net Metering Concept

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ABSTRACT

The research provides a novel model for active distribution network expansion planning that takes into account microgrid integration and numerous possibilities for boosting capacity, modifying feeders, and determining microgrid topology in islanded operating mode. The model considers the present value of network and microgrid installation, maintenance, and operating expenses, as well as distributed generating unit costs [1]. The suggested mixed integer nonlinear model has been successfully simulated and evaluated on a test network. The research describes a deep-learning-based clustering strategy for reliably classifying energy users based on usage patterns in unlabelled data, which employs an autoencoder for dimensionality reduction and clustering [2]. The suggested technique improves load profiling in smart grid analytics, giving useful information for utilities and stakeholders seeking to optimise power network operations. The study proposes HEDGE, an open-source tool for producing realistic domestic energy statistics such as PV generation, household electric loads, and electric car consumption and availability characteristics. HEDGE tackles a data gap in home distributed energy resource characterisation and coordination research, particularly for data-driven approaches such as machine learning-based forecasting and reinforcement learning-based control. The technology provides data sequences that correspond to real-life behavioural clusters and profile magnitudes, allowing researchers to efficiently investigate the energy profiles of specific residences [3]. Localised Demand Control (LDC) is a control system strategy for managing the integration of distributed energy resources into the traditional electrical grid, addressing issues such as demand fluctuation and temporal differences between generation and consumption schedules. The LDC system uses a power line carrier frequency signal to coordinate flexible energy resources so that they follow a chosen demand curve at the distribution transformer level. It has been successfully deployed in a 5-house microgrid, resulting in improved system load factor and enhanced hosting capacity for electric cars and solar photovoltaic panels [4]. The research paper describes a control approach for reactive compensation and power demand control in distribution circuits powered by renewable energy sources, intending to reach an agreement on compensation requirements for the whole circuit. The suggested method is accompanied by a mathematical demonstration of the closed-loop system's convergence and has been shown to efficiently manage reactive power and power demand in distribution circuits with significant renewable energy penetration [5].

Keywords— Microgrid, HEDGE, LDC, Power, etc.

I. INTRODUCTION

In today's power system architecture, active distribution network expansion planning is essential. We need to talk about how to integrate microgrids into these networks. The new model presented in this paper offers a range of options for modifying feeders, load shedding, replacing conductors, adding new substations, allocating and utilising distributed generation units, and figuring out how microgrids are structured in islanded operation mode. The model considers the present value of the total costs of network and microgrid construction, maintenance, and operation, as well as expenses associated with distributed generating units [1]. The challenge of properly grouping power users based on usage trends in unlabelled data from smart metres. Traditional clustering techniques struggle in high-dimensional areas, resulting in less accurate results and higher computing demands. The study presents a deep-learning-based clustering technique that uses an autoencoder for dimensionality reduction and clustering, hence boosting load profiling in smart grid analytics. The proposed technique divides the optimisation of reconstruction and cluster loss, spanning the gap between clustering quality and reconstruction efficiency. The approach's performance is rigorously evaluated by comparing it to traditional and cutting-edge algorithms using real-world smart metre data, and a full comparison analysis is presented against five typical dimension reduction strategies used in high-dimensional clustering [2].

The difficulty of creating realistic household energy statistics for data-driven algorithms like machine learning-based forecasting and reinforcement learning-based control. The Home Electricity Data Generator (HEDGE) is an open-source application that creates realistic daily profiles of domestic PV generation, household electric loads, and electric car use and availability [3]. The difficulty of incorporating dispersed energy resources into the conventional electrical infrastructure. The temporal difference between generating and consumption schedules can cause demand peaks and troughs, system overloading, voltage violations, and a poor system load factor. The study offers Localised Demand Control (LDC) as a control system solution for managing various forms of flexible energy resources and coordinating power demand. At the distribution transformer level, the LDC system follows a preferred demand curve via a power line carrier frequency signal [4]. The introduction emphasises the growing use of renewable energy sources (RES) in distribution circuits and the necessity for smart grids to manage dispersed generation and control actuation. It discusses the implementation of smart-grid tactics as well as the notion of Smart Power Cells for decentralised decision-making to achieve shared control objectives. The introduction also emphasises the significance of energy storage devices, including hydrogen generation and fuel cells, in compensating for excess energy supply and facilitating the transition to a hydrogen economy.

Traditional methods for reactive compensation are described, as well as the use of Flexible AC Transmission Systems (FACTS) power electronic devices for power factor management [5].

II. METHODOLOGY

A. Case 1

This paper addresses how to solve optimisation problems in active distribution network expansion planning by using heuristic evolutionary methods like Genetic Algorithms, Artificial Immune Systems, Tabu Search, Particle Swarm Optimisation, and hybrid methods like PSO combined with Simulated Annealing [1].

B. Case 2

The research employs a deep-learning-based clustering strategy that includes an autoencoder for dimensionality reduction and clustering to properly cluster power users based on usage patterns in unlabelled datasets. The suggested technique separates the optimisation of reconstruction and cluster loss, increasing the accuracy of load profiles in smart grid analytics. The approach's performance is systematically evaluated by comparing it to conventional and cutting-edge algorithms based on real-world smart metre data [2].

C. Case 3

The article introduces the Home Electricity Data Generator (HEDGE), an open-source programme that generates realistic domestic energy data such as PV generation, household electric loads, and electric car usage and availability profiles. The data pre-processing stages are described, including the completion of partial data sequences and the grouping of profiles into behaviour clusters [3].

D. Case 4

Specific Demand Control (LDC) is a control system strategy for managing flexible energy resources andcoordinating power demand. The LDC system controls the power demand of various types of flexible energy resources at the distribution transformer level by using a power line carrier frequency signal. The system's operation has been validated in a real 5-house microgrid with no negative impact on end-user comfort [4].

E. Case 5

The research suggests employing a discrete-time control rule to provide reactive compensation and power demand control in medium-voltage distribution circuits with renewable energy sources (RES). The control method employs electrolytic hydrogen production and fuel cell injection to regulate overall power demand while also distributing reactive power injection between substation and distributed generation (DG) units [5].

III. LITERATURE REVIEW

Reza Sheikhinejad et al,. The research provides a novel model for active distribution network expansion planning that takes into account microgrid integration and numerous possibilities for boosting capacity, modifying feeders, and determining microgrid topology in islanded operating mode. The suggested model is extremely efficient, having been successfully simulated and tested on a test network. To determine the goal function, the model considers the present value of the total costs of network and microgrid installation, maintenance, and operation, as well as the expenses associated with distributed generating units [1]. Abhimanyu Kumar et al,. This paper's contributions include the creation of a deep-learning-based clustering technique, improved load profiling in smart grid analytics, and practical insights for utilities and power sector stakeholders. The experimental results show that the proposed technique improves load profiling more than others, as evidenced by extensive load curve analysis and clustering validity indices [2].

Flora Charbonnier et al,. tackle the difficulty of creating realistic domestic energy data for research on residential distributed energy resource characterization and coordination. The lack of accessible data is considered as a key impediment to smart energy research, with data quality and formatting standards cited as obstacles. The Home Electricity Data Generator (HEDGE) is described as an open-access tool that bridges the gap by producing accurate daily profiles of domestic PV generation, household electric loads, and electric car use and availability. HEDGE allows researchers to effectively analyse the energy profiles of individual households and supports data-driven methodologies like machine learning-based predictions and reinforcement learning-based control. The authors emphasise the relevance of data-driven methodologies in home energy research, as well as the necessity for extensive information on EV usage, solar generation, and household consumption. The publication also discusses the privacy benefits of the HEDGE technique. Overall, the study introduces HEDGE as a useful tool for collecting realistic household energy data and discusses the issues of data availability and quality in residential energy research [3].

Ryan S Tulabing et al. This study presents a control system technique called Localised Demand Control (LDC) for managing the integration of distributed energy resources into the traditional electrical grid. The LDC system uses a power line carrier frequency signal to coordinate flexible energy resources at the distribution transformer level under a chosen demand curve. The LDC system's operation has been proven in a real 5-house microgrid, with no negative effects on end-user comfort.

Scaled-up modelling tests have indicated that the system load factor may be improved by up to 189%, with hosting capacity raised by 40% for electric cars and 16% for solar photovoltaic panels. This research underlines the LDC system's advantages over existing alternatives, such as its capacity to eliminate the requirement for a central server and substantial data collection from end-user devices, simplifying installation and lowering exposure to cyber security concerns [4]. The LDC system employs power line carrier frequency ripples, which are less vulnerable to hacking, resulting in a better degree of security.

Miguel Parada Contzen et al,. In addition to discussing the growing integration of renewable energy sources (RES) in distribution circuits, the study also highlights the role that smart grids play in controlling distributed generation and control actuation. The research suggests a straightforward and efficient control method that distributes reactive power injection and controls overall power demand through fuel cell injection and electrolytic hydrogen generation using a discrete-time control rule. A mathematical demonstration of the closed-loop system's convergence bolsters the efficacy of the suggested method. A case study of a 116-node distribution circuit with a considerable presence of renewable energy sources (RES) is used to evaluate performance and show how the suggested control method effectively regulates reactive power and power demand [5].

IV. FUTURE SCOPE

Future research might focus on optimising the allocation and utilisation of dispersed generating units in active distribution networks, taking into account their capacity, location, and type [1]. Advanced optimisation approaches, such as meta-heuristic algorithms, can be employed to solve the complicated mixed integer nonlinear model efficiently. Further study can investigate the applicability of the suggested deep-learning-based clustering technique in other areas outside power systems, such as healthcare, finance, or transportation, to solve comparable issues associated with high-dimensional data and nonlinear decision boundaries [2]. HEDGE may be used as a benchmarking tool to compare the effectiveness of various data-driven algorithms for household energy forecasting and control. The programme may be used to create long-term energy profiles to investigate the effects of seasonal changes and long-term trends on home energy consumption and generation [3]. The suggested Specific Demand Control (LDC) system has intriguing applications for integrating dispersed energy resources into the traditional electrical grid. Further study might focus on expanding the LDC system's deployment to bigger microgrids and even the microgrid level, to examine its efficacy and practicality in a broader environment. The LDC system may be expanded to include other types of flexible energy resources, such as wind power and energy storage devices, to improve overall system performance and boost the capacity for renewable energy sources [4].

Additional research may be done to improve the control method presented in the study for reactive compensation and power demand control in distribution circuits containing renewable energy sources (RES). To assess scalability and performance, the control technique may be expanded to larger-scale distribution circuits with more nodes and RES. The suggested method may be tested and verified in real-world distribution grids to determine its efficacy and feasibility [5].

V. CONCLUSION

The research provides a novel model for active distribution network expansion planning that takes into account microgrid integration and numerous possibilities for boosting capacity, modifying feeders, and determining microgrid topology in islanded operating mode. The report emphasises the importance of integrating renewable energy sources in microgrids, as well as the influence on active distribution network development planning, as a future research path. The study intends to improve load profiling in smart grid analytics and give practical insights for optimising power network operations. The suggested technique offers useful insights for utilities and others wanting to improve power network operations in smart grid analytics. The analysis emphasises the value of data-driven approaches in home energy research, as well as the necessity for extensive datasets on EV usage, PV generation, and household consumption. HEDGE is a great resource for academics investigating household energy profiles, and it tackles data availability and quality issues in the smart energy sector. The LDC system successfully coordinates various forms of flexible energy resources via a power line carrier frequency signal, resulting in a higher system load factor and more hosting capacity for electric cars and solar photovoltaic panels. Experimental and modelling findings demonstrate the LDC system's ability to reduce peak demand without sacrificing end-user comfort.

A method for managing power demand and reactive compensation in medium-voltage distribution circuits that uses renewable energy sources (RES). Using a discrete-time control rule, the proposed control strategy injects reactive power between distributed generation (DG) units and substations. It also uses fuel cell injection and electrolysis ofhydrogen to regulate overall power demand. To integrate and manage renewable energy sources inside the grid while preserving stability and dependability, the recommended control approach is helpful.

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