1.1 Probabilistic Power Flow in MATLAB

1.1.1 Introduction

The electric power sector is undergoing transformative changes driven by the increasing integration of renewable energy sources and the need for enhanced grid resilience. One of the significant challenges is to ensure that the power grid can reliably manage the variability and uncertainty associated with renewable energy generation. This requires advanced analytical techniques to predict and manage the fluctuating power flow within the grid.

Traditionally, power flow analysis has relied on deterministic methods, assuming precise knowledge of all system inputs and conditions. However, with the rise of intermittent renewable energy sources such as wind and solar photovoltaic (PV) systems, the need for probabilistic power flow (PPF) analysis has become more prominent. PPF methods account for the inherent uncertainties in generation and load, providing a more comprehensive understanding of potential scenarios and their impacts on the power system.

Renewable energy sources are often integrated at various points in the grid, including medium and low voltage levels, leading to distributed generation (DG). This integration transforms the grid from a passive to an active network, with power flow becoming bidirectional. In addition to DGs, other distributed energy resources (DERs) such as energy storage systems and demand response mechanisms contribute to the complexity and dynamism of the grid.

The adoption of PPF is crucial for several reasons. It enhances the ability to plan and operate the grid under uncertainty, improves the reliability and stability of the power supply, and supports the efficient utilization of DERs. PPF analysis helps identify potential issues such as voltage violations, thermal overloads, and system instability, allowing for pre-emptive measures to mitigate these risks.

MATLAB, a powerful computational tool, offers robust capabilities for conducting PPF analysis. It provides a range of functions and toolboxes designed for modelling, simulation, and analysis of power systems under uncertainty. Throughout this training session, we will explore the application of MATLAB and Matpower in performing probabilistic power flow analysis.

1.1.2 Training description

This document serves as a guide to understanding and performing both deterministic and probabilistic power flow analyses using MATLAB. The concepts and methods discussed are crucial for reskilling the workforce to manage the challenges posed by the integration of renewable energy sources into the power grid. The required software for this training are MATLAB and Matpower. The case study shown here is available with the Matpower install.

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1.1.3 Introduction to Power Flow Analysis

Power flow analysis is a fundamental tool used in the planning, operation, and optimization of power systems. It involves the study of the steady-state operation of a power system under various conditions. The primary outputs of a power flow study are the magnitudes and phase angles of the voltages at each bus and the real and reactive power flows in each transmission line. These outputs are essential for ensuring that the system operates within its limits, maintaining voltage levels within acceptable ranges, and ensuring that all components are neither overloaded nor underutilized, as well as for contingency planning.

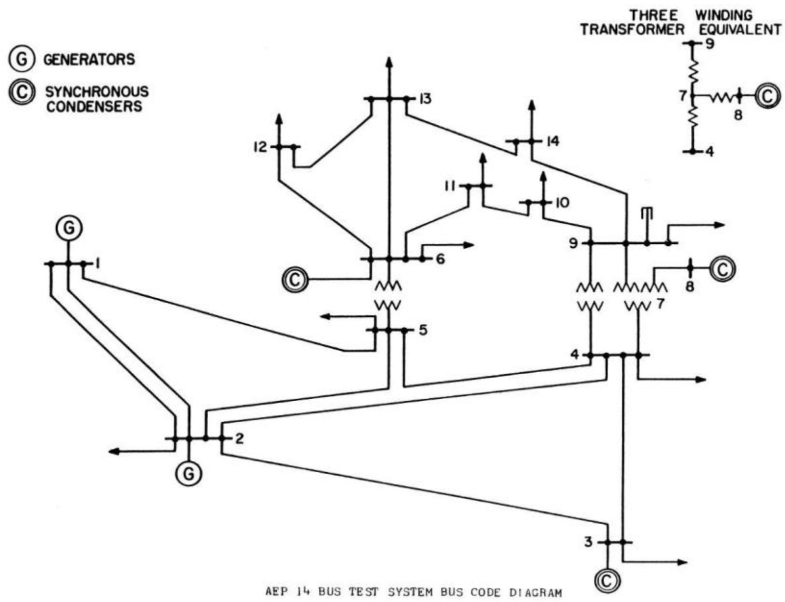

Figure 1. 14-bus test system used in this training.

1.1.4 Deterministic Power Flow (DPF)

The primary objective of DPF is to determine the steady-state operating conditions of a power system, including the voltage magnitudes and phase angles at each bus, as well as the real and reactive power flows through each transmission line by solving a set of nonlinear algebraic equations. DPF allows engineers to assess whether the system operates within acceptable voltage limits and ensure that power generation and load demands are balanced. DPF is a traditional and widely used method in power systems engineering that assumes precise and known inputs for system parameters. All loads, generation outputs, and network configurations are treated as fixed values without accounting for uncertainties or variations.

1.1.5 Performing DPF in MATLAB

To run a DPF analysis in MATLAB using Matpower, you need to prepare the input data, define the relevant power system parameters, and load the test network. These come pre-packaged in Matpower, so they just need to be loaded.

```
clc
clear all
```

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```
% set of constants to be used as named column indices into the bus, branch,
gen and gencost data matrices
define_constants;
% Load the test network
mpc=loadcase('case14');
% set and retrieve Matpower options
mpopt=mpoption('out.all',1,'verbose',1);
```

A wind turbine can be introduced into the system by specifying its bus number and capacity. For this tutorial, bus 10 with 10 MW can be used.

```
BusNum_WT= input('Enter the bus number for installing Wind turbine: ');
MWCap_WT= input('Enter the capacity (MW) of Wind turbine: ');

% Introduce Wind power at selected bus (as negative load)
mpc.bus(BusNum_WT,3)= mpc.bus(BusNum_WT,3) - MWCap_WT;
```

Run the power flow analysis and print the results.

```
[MVAbase, bus, gen, branch]=runpf(mpc,mpopt);
```

Store and plot the bus voltages. This will generate Figure 2 left.

```
% store bus voltages
DPF_BusVoltages=bus(:,VM);
save('DPF_BusVoltages.mat')

% plot bus voltages
plot(DPF_BusVoltages,'ro', 'LineWidth',2)
xlabel('Bus number')
ylabel('Voltage (pu)')
title('To satisfy the limits, Bus voltages should remain within between
0.90pu and 1.10pu ')
xticks([1:14])
grid on
```

Store and plot the power flows. This will generate Figure 2 right.

```
% store Power flows
DPF_Pflows=branch(:,PF);
save('DPF_Pflows.mat')


%plot absolute values of power flows
plot(abs(DPF_Pflows),'ro', 'LineWidth',2)
xlabel('Branch number')
ylabel('Power flow (MW)')
xticks([1:20])
xticklabels({'1-2','1-5','2-3','2-4','2-5','3-4','4-5','4-7','4-9','5-6','6-
11','6-12','6-13','7-8','7-9','9-10','9-14','10-11','12-13','13-14'})
xtickangle(45)
grid on
```

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Store real power loss at all branches and calculate total real power losses. This will be printed.

```
% extract real power loss at all branches
loss=get_losses(MVAbase, bus, branch);
Plvec=real(loss)


% print total real power losses
fprintf('Total power losses in the given test system are %4.4f
MW',sum(Plvec))
```

Save the workspace.

```
save('DPF_case14.mat')
```

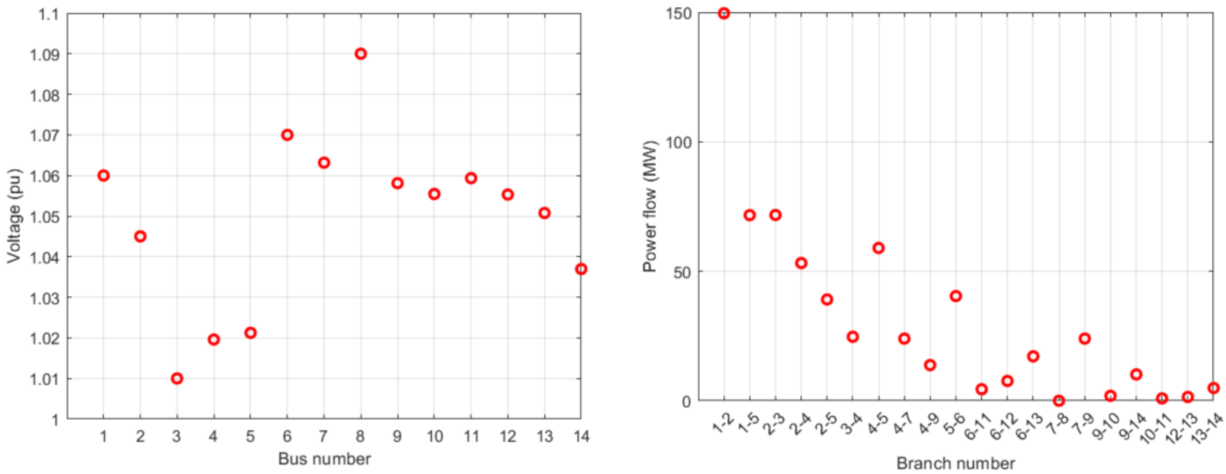

Figure 2. DPF results. Left: Voltages at every bus. Right: Power flow in every branch.

1.1.6 Probabilistic Power Flow (PPF)

Probabilistic Power Flow (PPF) builds upon traditional deterministic methods by accounting for the stochastic nature of power systems, especially with the increasing integration of renewable energy sources. Instead of using fixed values, PPF employs probability distributions to model these uncertainties, providing a range of possible outcomes and their probabilities, helping to assess the risk of overloading and voltage violations, as well as system planning and operational strategies.

1.1.7 Performing PPF in MATLAB

To perform a PPF, the uncertainties in power demand and wind generation need to be modelled using appropriate probability distributions.

A fixed number of simulations will be used. In this tutorial use, for example, 100 samples when prompted.

```
clc
clear all
TotSim = input('Enter the desired number of simulations (samples): ')
```

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Generate the **Power Demand Dataset** using the Gaussian distribution (with mean μ and standard deviation σ):

```
 % using normalised values

% set mean demand
MeanDemand= 1;
% set Standard deviation as 10% of mean
StdDevDemand=(0.1*MeanDemand);

% Create a Gaussian distribution object using the given parameter values
PdfDemand=makedist('Normal','mu',MeanDemand,'sigma',StdDevDemand);

% Generate random values from the above distribution
DemandDataset= random(PdfDemand,TotSim,1);
```

Generate the wind speed dataset using the Weibull distribution (with scale parameter α and shape parameter β); and then transform it into a wind power dataset using the speed-to-power function;

```
% scale parameter (m/s)
ScaleParameter=6.611;

% shape parameter
ShapeParameter=1.732;

% Create a Weibull distribution object using the given parameter values
PdfWindSpeed=makedist('Weibull','a',ScaleParameter,'b',ShapeParameter);

% generate random values from the above distribution
WindSpeedDataset= random(PdfWindSpeed,TotSim,1);

% technical parameters of wind turbine
Vci=3; % Cut-in Wind Speed in m/s
Vr=10; % Rated Wind Speed in m/s
Vco=25; % Cut-out Wind Speed in m/s
MWCapWindTurbine=1; % in MW

% intitalise Wind Power Dataset
WindPowerDataset=zeros(TotSim,1);

for SimNum=1:TotSim

    if Vci<=WindSpeedDataset(SimNum,1) && WindSpeedDataset(SimNum,1)<=Vr

WindPowerDataset(SimNum,1)=MWCapWindTurbine*((WindSpeedDataset(SimNum,1)^3-
Vci^3)/(Vr^3-Vci^3));

    elseif Vr<=WindSpeedDataset(SimNum,1) && WindSpeedDataset(SimNum,1)<=Vco
        WindPowerDataset(SimNum,1)=MWCapWindTurbine;

    elseif 0<=WindSpeedDataset(SimNum,1) && WindSpeedDataset(SimNum,1)<=Vci
        WindPowerDataset(SimNum,1)=0;
```

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```
    elseif Vco<=WindSpeedDataset(SimNum,1)
        WindPowerDataset=0;
    end
end
```

Load the relevant power system parameters, and the test network. These come pre-packaged in Matpower. The same case as the DPF will be used.

```
% set of constants to be used as named column indices into the bus, branch,
gen and gencost data matrices
define_constants;
% Load the test network
mpc=loadcase('case14');
% sets and retrieves Matpower options
mpopt=mpoption('out.all',0,'verbose',0);
```

Enter location (bus number) and capacity of the Wind Turbines (WT). For consistency with the DPF tutorial, bus 10 with 10 MW can be used.

```
BusNum_WT= input('Enter the bus number for installing Wind turbine: ');
MWCap_WT= input('Enter the capacity (MW) of Wind turbine: ');
```

Run the PPF analysis for the earlier specified number of simulations.

```
TotSim = input('Enter the desired number of simulations (samples): ')

%initialise output matrices for bus voltages and power flows
Nbus=size(mpc.bus,1);
Nbranch=size(mpc.branch,1);

PPF_BusVoltages=zeros(Nbus,TotSim);
PPF_Pflows=zeros(Nbranch,TotSim);

% store original bus load values (to be used at in the for loop...)
NominalBusLoads=mpc.bus(:,3);

for SimNum=1:TotSim

    % Calculate probabilistic loads at all buses
    SimBusLoads= NominalBusLoads .* DemandDataset(SimNum);

    % Introduce probabilistic loads at all buses
    mpc.bus(:,3)=SimBusLoads;

    % calculate probabilistic Wind power for selected buses
    SimWindGen= MWCap_WT * WindPowerDataset(SimNum);

    % Introduce probabilistic Wind power at selected buses (as negative load)
    mpc.bus(BusNum_WT,3)= SimBusLoads(BusNum_WT) - SimWindGen;

    % run power flow
    [MVAbase, bus, gen, branch]=runpf(mpc,mpopt);
```

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```
    %record voltages and flows
    PPF_BusVoltages(:,SimNum)=bus(:,VM);
    PPF_Pflows(:,SimNum)=branch(:,PF);

    Simulation_number= SimNum
end
```

Plot the DPF (red) and PPF (green) voltages with their legend for every bus. Figure 3 left.

```
p1=plot(PPF_BusVoltages,'go');
xlabel('Bus number')
ylabel('Voltage (pu)')
xticks([1:Nbus])
ylim([1 1.1])
grid on

%load DPF bus voltages from workspace and plot
load ('DPF_BusVoltages');
hold on
p2=plot(DPF_BusVoltages,'ro','LineWidth',2);
hold off
legend([p1(1), p2],{'PPF','DPF'})
```

Plot the DPF (red) and PPF (green) power flow in the branches with their legend. Figure 3 right.

```
p3=plot(abs(PPF_Pflows),'go');
xlabel('Branch')
ylabel('Power flow (MW)')
xticks([1:Nbranch])
xticklabels({'1-2','1-5','2-3','2-4','2-5','3-4','4-5','4-7','4-9','5-6','6-
11','6-12','6-13','7-8','7-9','9-10','9-14','10-11','12-13','13-14'})
xtickangle(45)
ylim([0 300])
grid on

%load DPF power flows from workspace and plot
hold on
load ('DPF_Pflows');
p4=plot(abs(DPF_Pflows),'ro', 'LineWidth',2);
hold off
legend([p3(1), p4], {'PPF','DPF'})
```

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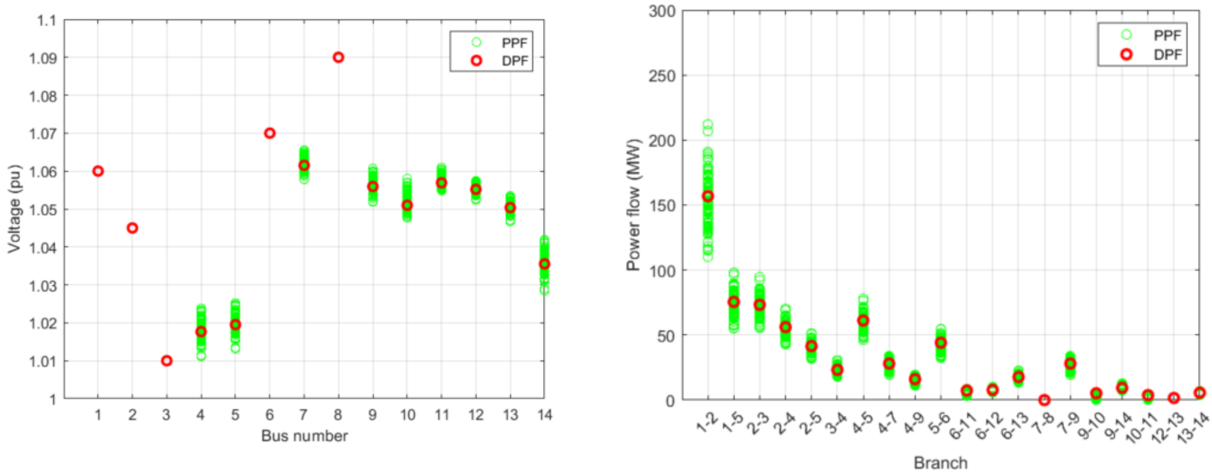

Figure 3. PPF results. Left: Voltages at every bus. Right: Power flow in every branch.

1.1.8 Comparison of results obtained from DPF and PPF

Deterministic Power Flow (DPF) and Probabilistic Power Flow (PPF) both aim to provide crucial information about the power system's operating conditions. DPF offers a single set of outcomes, detailing voltage magnitudes, phase angles at each bus, and real and reactive power flows in transmission lines based on fixed inputs, which may not accurately represent the behaviour of modern power systems with high levels of renewable energy penetration. In contrast, PPF addresses this limitation by providing probabilistic distributions of these same variables, reflecting the inherent uncertainties in load demands and generation outputs, especially from renewable sources. This makes PPF a more suitable approach for assessing the performance and risks in modern power systems.

1.1.9 Contribution to development of low carbon technologies, sustainability, and circularity

This topic holds significant importance in advancing the understanding, development and utilisation of low carbon technologies, promoting sustainability within the energy sector. By modelling inputs as probability distributions, PPF enhances risk assessment and decision-making for system planning and operation, identifying the likelihood of system violations and preparing for various scenarios. This approach leads to more robust strategies for managing potential risks and optimising resource allocation, thereby improving the overall reliability and efficiency of the power grid. Importantly, PPF also plays a significant role in the development of low carbon technologies and sustainability efforts. By accurately reflecting the impacts of renewable energy sources and dynamic load patterns, PPF helps in reducing the carbon footprint of power systems and promoting circularity in energy usage, thus supporting the transition to a sustainable and low-carbon energy future. PPF supports improved contingency planning and regulatory compliance by demonstrating the system's capability to handle uncertainties and mitigate associated risks. This is essential for

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integrating advanced technologies and demand response programs, which contribute to a more flexible and resilient grid.

Deterministic Power Flow (DPF) and Probabilistic Power Flow (PPF) both provide insights into power system operations, but PPF accounts for uncertainties in load and generation, making it more suitable for modern grids with renewable energy. PPF uses probability distributions to improve risk assessment, decision-making, and resource allocation, enhancing grid reliability and efficiency. PPF also supports contingency planning and regulatory compliance, aiding the integration of advanced technologies and demand response programs. Importantly, PPF contributes to low carbon technologies, sustainability, and circularity by accurately modelling renewable energy impacts, thus reducing the power system's carbon footprint.

1.1.10 Highlight on application in industry

This tutorial, using MATLAB and Matpower, equips engineers and researchers with the tools to design and operate sustainable power systems, promoting the efficient use of renewables and supporting the transition to a low-carbon, circular economy. By mastering PPF techniques in MATLAB, engineers and researchers can better address the challenges posed by the integration of renewable energy sources, ensuring a sustainable and resilient power grid for the future, especially as the integration of renewable energy sources increases. Utilities and grid operators use PPF to manage the variability and uncertainty of wind and solar power, optimising their placement and operation. This enhances grid efficiency and helps achieve renewable energy targets.

PPF is also essential for maintaining grid reliability and stability. By assessing the probability of voltage violations and thermal overloads, operators can develop robust contingency plans and operational strategies. This is critical for ensuring a stable power supply during peak loads or unexpected disruptions. In grid planning and expansion, PPF provides insights that guide investment decisions. By evaluating a range of future scenarios, utilities can prioritise projects that enhance resilience and support low-carbon technologies, leading to more strategic and cost-effective investments. Furthermore, PPF aids in regulatory compliance and risk management. It helps utilities demonstrate their capability to handle modern power system uncertainties, ensuring adherence to industry standards and maintaining public trust.

Overall, PPF supports a sustainable, reliable, and efficient power system. Using tools like MATLAB and Matpower for PPF analysis, industry professionals can navigate the complexities of modern grids, drive the development of low-carbon technologies, and contribute to global sustainability efforts.

1.1.11 Contribution to development of skills and competences

Training on probabilistic power flow analysis enhances essential skills and competences in the power industry. By working with PPF, engineers and researchers improve their understanding

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of power system complexities and learn to manage uncertainties in renewable energy sources. Proficiency in advanced computational tools like MATLAB and Matpower is developed, enhancing technical skills necessary for real-world applications.

PPF analysis also improves critical thinking and problem-solving abilities by requiring the interpretation of probabilistic results and informed decision-making about system operations. This analytical approach improves understanding of power system dynamics and grid management, essential for maintaining reliability and efficiency. The hands-on experience gained through PPF analysis prepares professionals to lead the power industry towards a more sustainable and resilient future, making them valuable assets in the evolving energy landscape.

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