DC-AC Tool: Fully Automating the Acquisition of the AC Power Flow Solution

Bin Wang and Jin Tan

National Renewable Energy Laboratory

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List of Acronyms

PF	Power flow
NREL	National Renewable Energy Laboratory
WECC	Western Electricity Coordinating Council

Executive Summary

The objective of this study is to develop an automated tool for achieving a converged AC power flow solution from any dispatch determined using a DC model-based optimal power flow. The entire process is free of human intervention. Often in practice, even with a DC power flow solution, acquiring the solved AC power flow solution can be challenging, especially during the planning stage. It is also difficult to distinguish the unsolved cases from diverging iterations. In the past, system planners have largely relied on making manual adjustments to approach the desired power flow condition, using lots of engineering heuristics.

This study proposes a systematic method and develops a tool, called the DC-AC tool, to first achieve a solvable AC power flow case by modifying the power flow condition and then to try to track the AC power flow solution while gradually removing the adopted changes. If all adopted changes can be completely removed, then the original AC power flow solution is obtained. Otherwise, insights into actionable controls are derived to help in operation and planning. Currently, this tool has been implemented in Python using Siemens PTI PSS/E as the power flow solver, where adjusting the generator terminal voltage set point or installing new reactive power support are considered as two approaches to try to turn a non-solving power flow into one that converges and solves. In the future, additional approaches could be considered, including the operation of tap-changing transformers, switching of shunt devices such as capacitors, and the redispatch of active power.

The developed software tool has been made free and publicly available at https://github.com/NREL/DC2AC.

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1 Background

1.1 Power Flow Equations

Power flow equations are a set of algebraic equations used to define the steady state of a power system under given loading conditions and generation dispatch. Solving power flow equations has been a common routine in daily power system operation and short- or long-term planning and in most research related to power system steady-state and dynamic performance, e.g., market design, economic dispatch, unit commitment, and transient stability simulation and analysis.

Power flow equations are formulated by applying Kirchhoff's current law and Kirchhoff's voltage law to the equivalent circuit of all elements in a power grid, usually represented in the nodal formulation. Generally, there are four electrical quantities associated with each bus in a power grid: bus voltage magnitude, V; bus voltage angle, θ; active power injection, P; and reactive power injection, Q. According to the electrical characteristic of the connected elements, buses can be categorized into three types: PQ bus, PV bus, and slack bus. For each of the three types, two electrical quantities are known, while the other two are unknown, as shown in Figure 1. For example, for PV buses, the P injection is controlled to follow the dispatch, whereas the terminal bus voltage magnitude, V, is usually regulated at a given set point by automatic voltage regulation; therefore, P and V are two known and fixed quantities, whereas Q and θ are the two unknown quantities to be solved from power flow equations. For a power grid with N buses, there are $2N$ unknowns and $2N$ equations to solve for them. Among these $2N$ equations, the power (or current) balance equations about the PQ and PV buses are called the power flow equations.

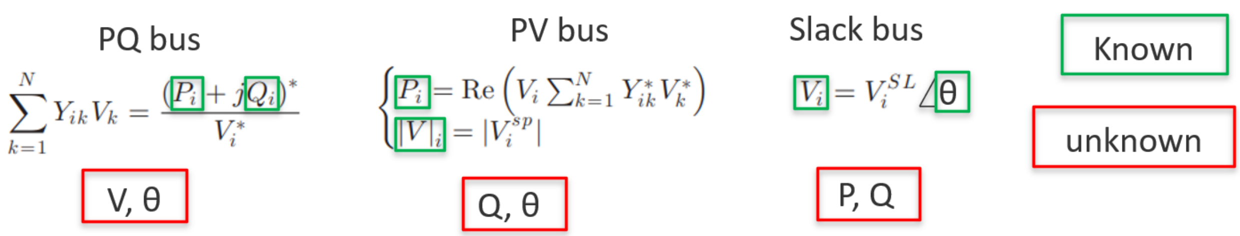

Figure 1. Knowns and unknowns in power flow equations

Power flow equations can be written using either polar or Cartesian coordinates and using either power balance or current balance, depending on the need. For example, if using polar coordinates and power balance, the resulting power flow equations for bus i are as follows:

$$0 = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})$$

$$0 = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik})$$

where P_i and Q_i are, respectively, the net active and reactive power injected at bus i; G_{ik} and B_{ik} are, respectively, the real and imaginary parts of the entry in the bus admittance matrix, Y_{BUS}, corresponding to the i^{th} row and k^{th} column; and θ_{ik} is the difference in voltage angle between the i^{th} and k^{th} buses, i.e., $\theta_{ik} = \theta_i - \theta_k$.

1.2 Iterative Solutions to Power Flow Equations

Although there are several noniterative solution methods, some of which are listed in Table 1, the power industry still widely uses the iterative solution methods, such as the Newton-Raphson method and the fast-decoupled method.

Table 1. Noniterative Power Flow Solution Methods

Name	Related Paper
Series power flow	Sauer (1981)
Gröbner basis	Ning et al. (2009)
Holomorphic embedding	Trias (2012); Wang, Liu, and Sun (2018)

Iterative solution methods always require an initial condition to start the iteration, with the hope of being able to converge to the final solution, if it exists, over iterations. The "quality" of the initial condition largely depends on the closeness to the final solution, if it exists. A bad initial condition could lead to a divergence, i.e., not being able to approach the final solution even if a solution exists; therefore, adopting a good-quality initial condition is key to the successful application of an iterative solution method to solve power flow equations.

In the practical operation and planning of power systems, it is not always easy to acquire a good initial condition for power flow calculations. During normal operation, the state estimation program is regularly conducted, e.g., every 5 minutes, such that the previous converged case can always be used as a good initial condition to calculate the next recent power flow problem. But the planning problem is different. Power system planning aims to evaluate system performance at forecasted loading and optimized dispatch conditions, which usually presents power flow problems without having a good initial condition. In such cases, a DC power flow solution, which is based on simplified and linearized power flow equations, can be used to help with the convergence of many planning cases. Still, there could be cases where the divergence issues are encountered. In addition, power flow divergence can be an issue for black-start and restoration studies when there are significant changes in system conditions, e.g., topology, dispatch, and loading.

Power system engineers have put other efforts to solving these diverging power flow problems and to gaining some insight into regaining power flow solvability, e.g., by modifying the dispatch, the specification of line ratings, and even the unit commitment. These efforts are mostly manual, involving trial-and-error processes and requiring significant engineering judgements.

1.3 Motivation and Scope of Work

Optimal power flow-based economic dispatch—i.e., production cost simulation—of power systems always adopts the DC power flow model, which is a simplified and linear approximation of the original AC power flow problem. This is mainly because DC power flow produces a unique solution, even if the associated AC power flow problem may not have a viable solution. To fully evaluate the reliability of a steady state produced by economic dispatch, however, the AC power flow solution is needed to initialize the dynamic simulation. This is not a simple task because of the divergence issue of all the iterative solution methods, as discussed in Section 1.2. Practically, when encountering power flow divergence issues, power system engineers usually need to make manual adjustments—such as to solution parameters, initial conditions, generation dispatch, voltage regulation, network topology, and reactive power support, among others. This is done step-by-step based on experience and heuristics to gradually and hopefully approach the solution of the underlying AC power flow problem, if it exists. There are also several approaches to address the solution failures that demand for changes to the target power flow problem, leading to solving a different problem (Abbas 2012). This is a tedious and time-consuming process even for experienced engineers.

This work aims to develop an automated tool, called the DC-AC tool, to solve power flow problems, specifically to (1) automatically converge to the AC power flow case, if solvable, from the DC power dispatch without human intervention; and to (2) provide insight into convergence if it is insolvable. Section 2 introduces the methodology of the DC-AC tool, and Section 3 presents numerical results on a simplified Western Electricity Coordinating Council (WECC) 240-bus system using the 1-year scheduling results, including a total of 8,784 power flow cases.

2 DC-AC Tool

2.1 Methodology

The key idea of the tool to handle diverging power flow cases is to first find a solved AC power flow by systematically changing the case and then to gradually eliminate those changes by solving a series of power flow cases with or without modifying certain specified conditions of the power flow problems, e.g., the voltage set point of the generator bus and the loading level of the load bus.

Any physical power system can lose its steady state because of either a lack of sufficient reactive power support or a load demand that is too high, which pushes the system beyond the nose point on the P-V curve. Inspired by these two mechanisms, to acquire a solved AC power flow solution, we consider either adding temporary fictitious generators with zero P injection and unlimited Q capacity or reducing the system loading. We conducted extensive numerical studies and found that these two procedures would always produce a solved AC power flow case. Details are presented in the next section using a flowchart.

2.2 Flowchart

Figure 2 shows a flowchart of the DC-AC tool, which contains seven steps; eight IF statements; and six possible results, among which five will bring solved power flow cases, marked in green, and one will lead to an insolvable power flow, marked in orange. More details about these steps, the IF statements, and the results are explained in the following.

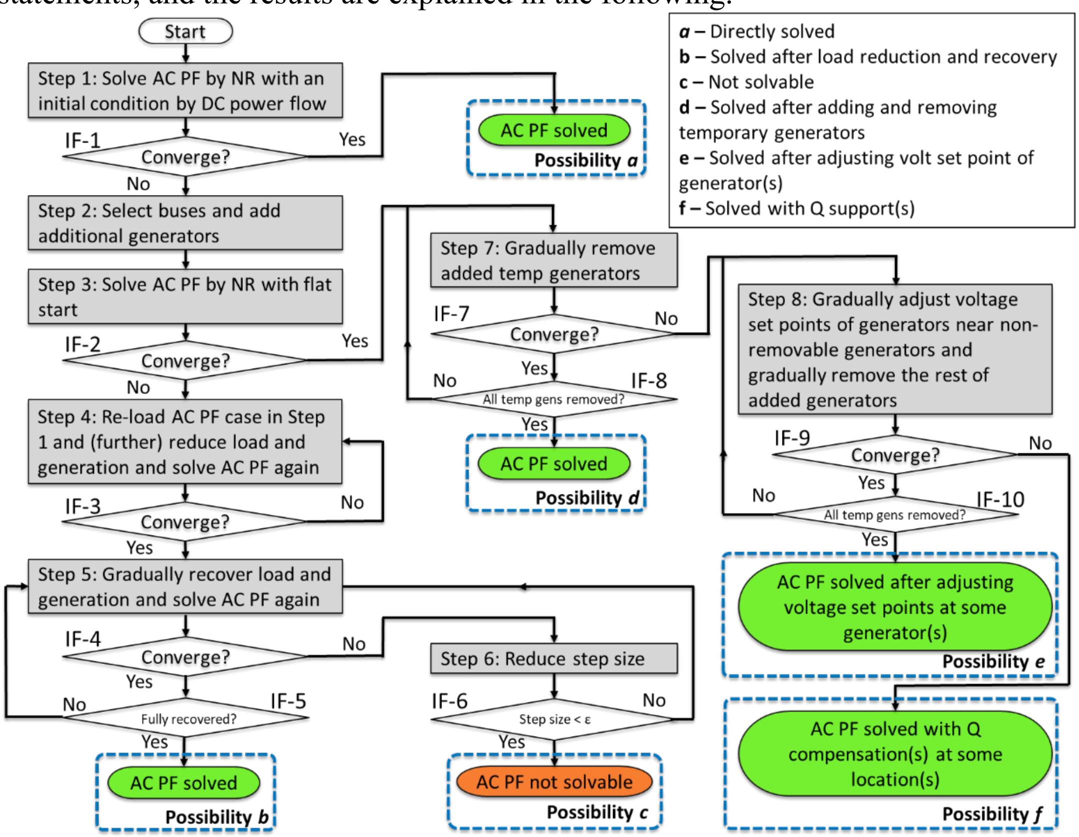

Figure 2. Flowchart of the DC-AC tool

Given an AC power flow problem, **Step 1** is to try to solve the AC power flow by the Newton-Raphson method with an initial condition provided by the DC power flow solution. The convergence of this Newton-Raphson solution is checked in **IF-1**. If the convergence is met, then the given AC power flow can be **directly solved** (**possibility *a***). For any well-designed power system, most of the planned operating conditions from the scheduling with properly selected constraints should be directly solved. The following discusses when the convergence is not met in **IF-1**.

For diverging power flow cases in **Step 1**, we want to first modify the power flow and obtain a converged solution, and then we want to gradually remove that modification to recover the original power flow solution. Inspired by Birchfield, Xu, and Overbye (2018), the modification we adopted in **Step 2** is adding temporary fictitious generators to selected buses in the system with zero P and unlimited Q capacity. By doing this, we hope to find a power flow solution at the target loading condition without the convergence issue (or static voltage instability) caused by a lack of reactive power. The criterion for selecting the buses to connect temporary fictitious generators is to identify and select the high-voltage bus in each substation. It was reported that these temporary fictitious generators should not be added too densely. Otherwise, power flow could converge to undesirable solutions (Birchfield, Xu, and Overbye 2018), e.g., a solution with huge Q transfer in a certain local area between electrically-close generating units. As stated, the P set point of these added generators takes zero, whereas the voltage set point is determined based on the type of the connected bus: (1) for generators added to a PV bus, the voltage set point will be the original one specified by the previously existing generators; (2) for generators added to a PQ bus, the voltage set point is set to be 1.0 per unit. The AC power flow is solved in **Step 3** by the Newton-Raphson method with all temporary fictitious generators in place, and it is initialized with the DC power flow solution, including the voltage angles, the dispatch of the existing generators, and a certain compensation of network loss, e.g., 1%–3%. It was also reported that the AC power flow with such an initial condition would most likely converge, even for a system with up to 10,000 buses (Birchfield, Xu, and Overbye 2018).

Although **steps 2 and 3** can help to converge most diverging power flow cases after **IF-1**, there is still a possibility that a divergence is met in **IF-2**. In such a case, it is most likely that the target loading is beyond the nose point on the P-V curve, thus leading to the nonexistence of any power flow solution. To confirm this or to find the solution if it ever exists, **Step 4** is performed by reducing the loading and the generation to acquire a solved case, and then **Step 5** is taken to recover the loading and the generation to approach the target loading.

In **Step 4**, we reload the original AC power flow problem in Step 1 without any temporary fictitious generators, and then we reduce the total loading and generation proportionally with a small step, e.g., 5%, of total load/generation. With the reduced loading and generation, the new AC power flow is solved by the Newton-Raphson method using the DC power flow solution as the initial condition. If Newton-Raphson iterations do not converge in **IF-3**, further reductions in the loading and generation will be applied, and the AC power flow will be solved again by the Newton-Raphson method, with the DC power flow solution reloaded as the initial condition. It is believed that the algorithm will always exit the loop formulated by **Step 4** and **IF-3** because with a large enough reduction in the load and generation (e.g., 100% reduction), the AC power flow solution (flat-start solution) can always be gained.

The purpose of **Step 5**, **Step 6**, **IF-4**, **IF-5,** and **IF-6** is to track the AC power flow solution by gradually recovering the loading to the target loading in the original AC power flow in **Step 1**. Because a solved AC power flow has been obtained from **Step 4** and **IF-3**, this can serve as a good initial condition to start **Step 5** when applying the Newton-Raphson method to the new AC power flow problem with a certain amount of loading and generation recovered, e.g., 1% or 100 MW depending on the system total load and its stress level. The convergence of the Newton-Raphson iterations is checked in **IF-4**. If the convergence is met and the reduced load/generation have not been fully recovered in **IF-5**, then we continue recovering more loading and generation, e.g., by another 1% or 100 MW, we use the most recently solved AC power flow solution as the initial condition, and we apply the Newton-Raphson iterations again. If the convergence in **IF-4** is not met, then we reduce the amount of loading and generation to be recovered, the named step size in **Step 6**, and we go to **Step 5** using the last solved AC power flow solution as the initial condition. If the target loading in the original power flow in **Step 1** can be reached with a converged AC power flow solution—i.e., the fully covered condition in **IF-5** is met—then we have **solved the AC power flow after the load reduction and recovery** (**possibility *b***), and we have obtained the AC power flow solution. If the convergence in **IF-4** is not met and the step size is smaller than a prespecified threshold, ε, e.g., $\varepsilon = 1$ MW, then this case is **not solvable** (**possibility *c***), and it is concluded that the original AC power flow problem in **Step 1** is not solvable, whereas reducing the loading and generation allows for a solved power flow case.

Then, we return to **IF-2** and discuss the situation where the AC power flow in **Step 3** can be solved with the additional temporary fictitious generators. Next, we start from that solved AC power flow solution; we gradually remove the added generators and solve the AC power flow after every change using the last solved AC power flow solution as the initial condition; and we check whether we can completely remove all the added generators through **Step 7**, **IF-7,** and **IF-8**. If all temporary fictitious generators can be removed and there is no divergence issue in **IF-7**, then the given AC power flow is solved, and we have **solved the AC power flow after adding and removing the temporary fictitious generators** (**possibility *d***). If a diverging AC power flow is encountered before completely removing all the temporary fictitious generators, we will go to **Step 8** and check whether we can remove those generators by adjusting the voltage set point of the existing PV buses.

When beginning **Step 8** from **IF-7**, the solved AC power flow problem we have has a few temporary fictitious generators compensating Q at certain locations, which do not exist in the original AC power flow problem. We have tried but cannot directly remove them and reach another solved AC power flow solution. To remove these Q compensations, we can adjust the voltage set point at the existing PV buses: If a temporary fictitious generator injects Q into the grid, showing that the original AC power flow problem might need more Q to become solvable, we can consider increasing the voltage set point at the nearby existing PV buses such that generators connected to these PV buses (or nearby PV buses) can inject additional Q into the grid, and the temporary fictitious generator can hopefully be removed without causing AC power flow divergence; and vice versa. If all temporary fictitious generators can be gradually removed and there is no divergence issue in **IF-9**, then the given AC power flow is solved with the modified voltage set point at some PV buses, and we have **solved the AC power flow after adjusting the voltage set point of some generator(s)** (**possibility *e***).

But there is still a possibility that all Q-V curves are above zero, where Q represents the Q injection at the temporary fictitious generator, and V represents the voltage magnitude of the existing PV buses. If this happens, the Q compensation at the location with the temporary fictitious generator is necessary to approach a solved AC power flow case, and the divergence is encountered in **IF-9** before completely removing all the temporary fictitious generators. In such a case, we have **solved the AC power flow with Q compensation(s) added at some location(s)** (**possibility *f***).

2.3 Remarks

The objective of this DC-AC tool aims to fully automate, without any human intervention, acquiring a solved AC power flow solution for scheduling cases that might not have good initial conditions. If the AC power flow is solvable, then the DC-AC tool is expected to identify that solution. If the AC power flow in not solvable, then the DC-AC tool can provide meaningful actionable information to enable a solvable case as well as the resulting AC power flow solution under those controls. A few remarks are provided as follows:

- The DC power flow solution is used as an initial condition for any AC power flow problems involved in this tool that do not have any other better guess of their solution. That said, any other guess of the AC power flow solution can also serve as an alternative for this purpose.
- The process consisting of **Step 5**, **IF-4,** and **IF-5** is equivalent to a numerical continuation power flow from a solvable light-loading condition to the target loading condition. This process can answer the question of whether the AC power flow at the target loading is solvable or not, which is useful information. But this process is not able to provide insightful actionable information to approach a solvable AC power flow case if the original AC power flow is not solvable; therefore, we first take **Step 2** and **Step 3** to check whether the lack of Q compensation contributes to the AC power flow divergence.
- For **possibilities *a*** (directly solved), ***b*** (solved after load reduction and recovery), and ***d*** (solved after adding and removing the temporary generators), the original AC power flow problem can be solved, and there is no need for any controls, either in planning or operation, to achieve the solvability.
- For **possibility *e*** (solved after adjusting the voltage set point of the generator(s)), the original AC power flow problem can be solved with modifications to the voltage set point at some PV buses. This could be useful information for operation.
- For **possibility *f*** (solved with Q support(s)), the original AC power flow problem can be solved with Q compensation at certain buses. This could be useful information for planning.
- For **possibility *c*** (not solvable), the original power flow with its specified loading and generation dispatch cannot be solved, i.e., an AC power flow solution does not exist. To make it a solvable case, it is necessary to either reduce the loading (which will always lead to a solvable AC power flow case; this has been investigated in this tool) or redispatch the generation (which might or might not lead to a solvable AC power flow case; this has not been included in this tool). Other potentially useful information can be mined from the solved AC power flow problem with reduced loading/generation to guide the re-dispatching or re-specification of line limits, e.g., the overloaded lines or lines with

the least margins in MVA identified from the solved AC power flow problem with reduced loading/generation.

3 Numerical Results

The methodology introduced in Section 2 has been implemented using Python and PSS/E. The test system and cases are introduced in Section 3.1. The test results are presented in Section 3.2. All tests in this project were performed on a laptop with Intel dual-core i7-8665U at 1.90 GHz, 2.11 GHz, and 16.0 GB RAM.

3.1 Test System and Cases

A reduced WECC 240-bus power system developed by the National Renewable Energy Laboratory (Yuan, Biswas, Tan and Zhang 2020) from (Price and Goodin 2011) is adopted to test the proposed methodology. The one-line diagram of this 240-bus system is shown in Figure 3. This system has 243 buses, 146 machines, 139 loads, 7 switched shunts, 329 AC lines, and 122 two-winding transformers. The base case has a total load of 81463.84 MW and a total generation of 83858.68 MW. The hourly scheduling in 1 year gives 8,784 power flow problems (corresponding to 1 year with 366 days).

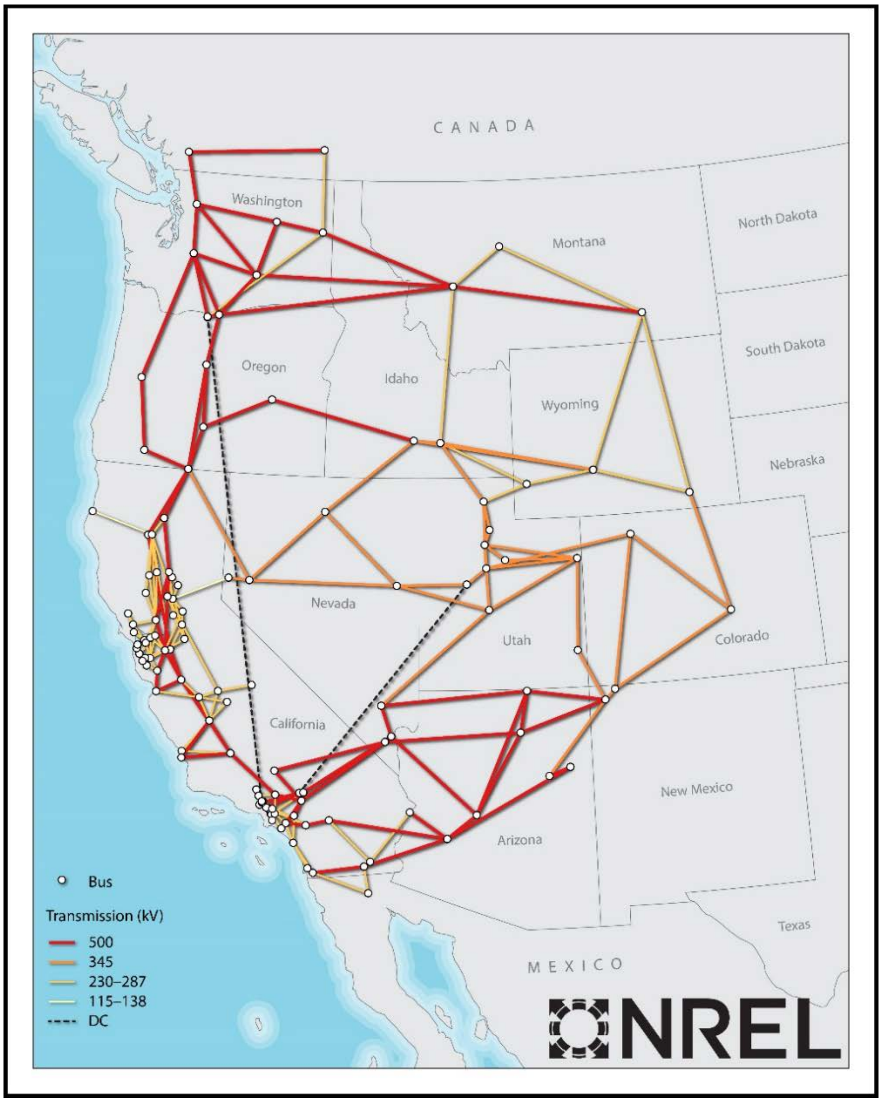

Figure 3. One-line diagram of a simplified WECC 240-bus system

3.2 Test Results

For comparison, we applied a methodology using only **Step 1** and **IF-1**, which could classify all 8,784 cases into two groups: 8,767 solved cases and 17 unsolved cases. The following discusses how the methodology proposed in this work handles these 17 unsolved cases and how it helps generate more solved cases.

First, 126 buses are selected to add temporary fictitious generators. These buses are listed in Table 2. These buses were selected to include only one bus from all buses in the same substation to try to avoid large local reactive power transfers (Birchfield, Xu, and Overbye 2018); however, if a large reactive power transfer is observed in certain local areas in the system, this means that there are too many added temporary fictitious generators. Because these added generators regulate their terminal voltage by adjusting their reactive output, if the voltage set points between the local generators are large, then large reactive power transfers will appear. To resolve this issue, we simply exclude some of the generators where large reactive power is observed.

After being processed by the proposed DC-AC tool, all 17 cases are eventually solved; see results in Table 3. In terms of run time, it takes approximately 17 minutes for the proposed DC-AC tool to scan all 8,784 power flow problems. Specifically, among these 17 unsolved cases, 13 become solved as a result of **possibility *d*** (solved after adding and removing the temporary generators), 1 becomes solved as a result of **possibility *b*** (solved after reducing and recovering the load), and the remaining 3 become solved as a result of **possibility *e*** (solved after adjusting the voltage set point of the generator(s)). The 14 solved cases from **possibilities *b*** or ***d*** are solvable at their target loading without any modifications on the power flow condition. The 3 solved cases from **possibility *e*** are solvable after adjusting the voltage set point on some selected PV buses. The modified voltage set points are listed in Table 4.

Table 2. Selected 126 Buses to Add Temporary Fictitious Generators

1003, 1004, 1032, 1101, 1102, 1201, 1202, 1301, 1302, 1401, 1402, 1403, 2000, 2100, 2201, 2203, 2301, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2410, 2501, 2503, 2600, 2601, 2602, 2603, 2604, 2608, 2609, 2610, 2611, 2613, 2901, 2902, 3101, 3102, 3103, 3105, 3201, 3202, 3203, 3204, 3205, 3301, 3302, 3305, 3401, 3402, 3403, 3404, 3405, 3501, 3601, 3701, 3801, 3802, 3803, 3806, 3891, 3901, 3902, 3903, 3904, 3905, 3906, 3907, 3908, 3909, 3910, 3911, 3912, 3913, 3914, 3915, 3916, 3919, 3920, 4001, 4002, 4003, 4004, 4005, 4006, 4007, 4101, 4102, 4103, 4201, 4202, 4203, 4204, 5001, 5002, 5003, 5004, 6101, 6103, 6201, 6202, 6205, 6301, 6302, 6305, 6403, 6404, 6501, 6502, 6503, 6504, 6505, 6507, 6508, 6509, 7001, 7002, 8001, 8002, 8003 and 8004

Table 3. Results of DC-AC Tool on Unsolved Power Flow Cases

Case #	Month	Day	Hour	Resulting Possibility from DC-AC Tool
1	2	8	9	Solved after adding and removing temporary generators (d)
2	2	8	10	Solved after adding and removing temporary generators (d)
3	3	6	8	Solved after adding and removing temporary generators (d)
4	4	1	8	Solved after adding and removing temporary generators (d)
5	4	4	4	Solved after adding and removing temporary generators (d)
6	4	6	1	Solved after adding and removing temporary generators (d)

Case #	Month	Day	Hour	Resulting Possibility from DC-AC Tool
7	4	8	20	Solved after adding and removing temporary generators (d)
8	5	10	5	Solved after adding and removing temporary generators (d)
9	5	15	17	Solved after adding and removing temporary generators (d)
10	5	19	5	Solved after adding and removing temporary generators (d)
11	10	8	21	Solved after adjusting the voltage set point of generator(s) (e)
12	10	31	4	Solved after adding and removing temporary generators (d)
13	10	31	16	Solved after adjusting the voltage set point of generator(s) (e)
14	10	31	18	Solved after adding and removing temporary generators (d)
15	11	2	15	Solved after load reduction and recovery (b)
16	12	8	19	Solved after adjusting the voltage set point of generator(s) (e)
17	12	11	11	Solved after adding and removing temporary generators (d)

Table 4. Summary of Modified Voltage Set Point

Case #	Month	Day	Hour	PV Bus	V Set Point Before	V Set Point After
11	10	8	21	2438	1.009	1.0419
13	10	31	16	6335	1.060	1.0955
16	12	8	19	2438	1.009	1.0227

To illustrate the process, we walk through the flowchart from Figure 2 using Case 11 as an example. In **Step 1**, the Newton-Raphson solver in PSS/E is first applied to the solution from the DC power flow produced by economic dispatch. In this case, however, the Newton-Raphson solver diverges, so we go to **Step 2** and add 126 temporary generators to the buses listed in Table 2. Next, we go to **Step 3** to try the Newton-Raphson solver again but with a flat start. This time, the Newton-Raphson solver converges with six iterations, such that **IF-2** will route us to **Step 7**. After entering **Step 7**, the solved AC power flow case has 126 temporary fictitious generators, and the loop consisting of **Step 7**, **IF-7,** and **IF-8** will try to remove these added generators and keep solving the AC power flow using the previous AC power flow solution as a starting point. This loop is able to remove nearly all of the fictitious generators while still being able to solve the resulting power flow. The exception are three temporary fictitious generators on buses 1202, 2404, and 4203 (which were PQ buses in the original power flow problem). These fictitious generators cannot be removed without causing power flow to diverge. Therefore, **IF-7** will move to **Step 8** to try to adjust the voltage set points at these three PV buses, using either the added temporary fictitious generators or generators from the original power flow model.

As listed in Table 5, these three temporary fictitious generators contribute a large amount of reactive power and regulate their bus voltages to be 1 p.u. For the temporary fictitious generator on Bus 1202, its reactive power output is -9999 MVAR (the lower Q limit), showing that this temporary fictitious generator absorbs 9999 MVAR that is produced by other generators in the system. Since reactive power flows from a higher voltage to a lower voltage, it is possible to reduce the reactive power absorption at Bus 1202, by increasing its voltage set point.

These adjustments are made in **step 8**, **IF-9,** and **IF-10** which automatically remove these three temporary generators by adjusting the voltage set points. Taking the generator at Bus 1202 as an example, three power flow problems are first solved, with slightly different voltage set points for generator 1202—i.e., 0.99, 1.00, and 1.01 p.u. With these three power flow solutions, we can fit a parabolic Q-V curve, where Q is the reactive output of the added temporary generator at bus 1202. Then, by solving for the voltage, V, such that Q(V)=0, we can find the desired voltage set point required for zero Q. With that desired voltage set point—1.067 p.u. in this case—the temporary fictitious generator 1202 is no longer contributing to the power flow, hence can be removed without affecting power flow convergence. For our example, Case 11, we can remove all three temporary generators, as described below. However, if in another case anything in this process does not work properly—such as if the power flow with a 0.99-p.u. or 1.01-p.u. voltage set point does not converge—we would exit the loop at IF-9, and we conclude the case as **possibility f** (solved with Q support(s)).

Like the temporary generator 1202, we can also remove the temporary generator at Bus 4203. Removing these two temporary fictitious generators does not require any modification of the original power flow conditions because these two buses are PQ buses in the original power flow. For the temporary generator 2404, however, it is impossible to achieve zero Q output from the temporary fictitious generator simply by adjusting its voltage set point. This is because the Q-V curve at 2404 is always above zero, and there is no intersection with Q=0. In this case, we instead modify the voltage set point of nearby PV buses (i.e., the original PV buses before adding the temporary fictitious generators). It is found that adjusting the voltage set point of Bus 2438 from 1.009 p.u. to 1.0419 p.u., as shown in Table 6, allows the power flow to fully converge.

Table 5. Q Output and Voltage Set Point of Temporary Fictitious Generators Before Step 8 for Case 11

Bus with Temporary Fictitious Generator	Voltage Set Point Before Change	Q Output of Temporary Fictitious Generator
1202	1.000	-9999 MVAR
2404	1.000	1544 MVAR
4203	1.000	-2501 MVAR

Table 6. Change in Voltage Set Points for Removing the Three Temporary Fictitious Generators in Table 5

Bus with Changed Voltage Set Point	Voltage Set Point Before Change	Voltage Set Point After Change
1202	1.000	1.067
2438	1.009	1.0419
4203	1.000	1.064

4 Concluding Remarks

This report presented the development of an automatic tool, called the DC-AC tool, which is completely free of human intervention, to acquire the AC power flow solution, if it exists, or to gain insight into the necessary control actions to achieve a solvable power flow solution to potentially implement in operation and/or planning. This software tool has been made free and publicly available on GitHub (NREL, 2022). Following are some observations and discussions on the potential improvements of this tool to be considered in the future.

- For the only case ending with **possibility *b*** (solved after load reduction and recovery), originally, we started from the solved AC power flow solution with all temporary fictitious generators added. We found that we were not able to remove all the temporary fictitious generators, and we observed a very large reactive power transfer locally among a few generators. This issue seems to be related to the phenomenon reported in (Birchfield, Xu, and Overbye 2018) when temporary fictitious generators are added too densely; therefore, it seems very possible that a smaller number of buses could be selected in **Step 2**, which could potentially reduce the run time of this tool.
- For these 8,784 power flow cases from the 1-year scheduling of the simplified WECC 240-bus system, it was also observed that some of the resulting voltage profiles seem problematic, where many voltages are either greater than 1.1 p.u. (up to 1.14 p.u.) or less than 0.9 p.u. (down to 0.82 p.u.). These voltage violations should be avoided since they likely violate inequality constraints desired in the optimal power flow problem used for scheduling. These violations are a result of the proposed DC-AC algorithm and could be fed back into the scheduling process to be resolved. Alternatively, it might be practical to tighten the tolerances in the original scheduling problem such that most of the expanded ranges from the DC-AC tool remain valid.
- Additional efforts in simulating the electromechanical dynamics of the system by incorporating dynamic data were also made during study, but they were not included in this report. We found that the following limits should be properly configured to ensure a clean case (i.e., flat rotor angles and zero rotor speed are expected under a no-disturbance simulation): (1) the selection of the swing bus, (2) the MVA base of all generators, and (3) both the static and dynamic Q limits of the solar generation and synchronous condensers.

Future work to potentially improve the proposed DC-AC tool includes the following:

- Consider control actions at other components, instead of only adjusting the voltage set point at generators or adding reactive power support from compensation devices such as capacitor banks, to achieve a solvable AC power flow case, including but not limited to tap-changing transformers and switched shunts.
- Adopt other noniterative power flow solution methods, e.g., the holomorphic embedding method, to gain more insight into the unsolved cases and to guide the control actions to achieve solvable AC power flow cases.
- For AC power flow cases ending with **possibility *c*** (we did not observe any in the tested 8,784 1-year scheduling cases on the WECC 240-bus system), develop a systematic way to redispatch the system to allow a higher system power transfer limit and potentially identify the dispatch for the maximum loading condition.

- Leverage parallel computing to run the DC-AC algorithm by solving multiple power flow cases simultaneously—for the most part they are already independent—to enhance performance.

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