World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:17, No:11, 2023

Digital Twin of Real Electrical Distribution System with Real Time Recursive Load Flow Calculation and State Estimation

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Open Science Index, Energy and Power Engineering Vol:17, No:11, 2023 publications.waset.org/10013381.pdf

Abstract—Digital Twin (DT) is a technology that generates a virtual representation of a physical system or process, enabling real-time monitoring, analysis, and simulation. DT of an Electrical Distribution System (EDS) can perform online analysis by integrating the static and real-time data in order to show the current grid status and predictions about the future status to the Distribution System Operator (DSO), producers and consumers. DT technology for EDS also offers the opportunity to DSO to test hypothetical scenarios. This paper discusses the development of a DT of an EDS by Smart Grid Controller (SGC) application, which is developed using open-source libraries and languages. The developed application can be integrated with Supervisory Control and Data Acquisition System (SCADA) of any EDS for creating the DT. The paper shows the performance of developed tools inside the application, tested on real EDS for grid observability, Smart Recursive Load Flow (SRLF) calculation and state estimation of loads in MV feeders.

Keywords—Digital Twin, Distribution System Operator, Electrical Distribution System, Smart Grid Controller, Supervisory Control and Data Acquisition System, Smart Recursive Load Flow.

I. INTRODUCTION

THE inexorable shift of the electrical power system towards a sustainable and renewable energy-focused paradigm is accompanied by considerable versatility as well as notable challenges [1]. A corresponding shift in operation strategies, embracing more intelligence and digitization is required to achieve an optimal, reliable, and secure operations at all levels [2]. This objective can be achieved by a system empowered by innovative solutions and advanced algorithms enabled with handling real time data with faster computation methods rather than iterative approaches. Time restriction in power system management is crucial, so faster analysis and simulations of various hypothetical scenarios in real time is required. To address this need, efforts have been made to create a DT of EDS.

DT technology entails creating a virtual counterpart of a physical system or process, enabling real-time monitoring, analysis, and simulation [3]. This concept has transcended industries such as manufacturing, healthcare, and energy [4]. It hinges on merging historical and real-time data with predictive analytics, offering comprehensive insights into a system's dynamics. DT technology has gained significant attention in smart grids and EDS. The concept of a DT offers a virtual replica of a physical system, network structure, enabling real-time monitoring, analysis, decision making, and behavior within a digital environment [5]. Research into applying DTs to EDS has intensified due to their potential in optimizing grid management, fault detection, and predictive maintenance [6], [7]. Furthermore, the use of advanced algorithms and machine learning techniques within the DT architecture enables the prediction of system behavior, identification of potential faults, and optimization of operational strategies [8], [9]. These capabilities contribute to improved system reliability, energy efficiency, and effective asset management. Yet, some approaches in literature exhibit limitations such as dependence on proprietary software, inflexibility in adapting to diverse grid configurations, and constraints in real-time scalability.

Recent research has focused on addressing the challenges associated with DT implementation in EDS. This includes developing scalable and efficient algorithms for data integration, model updating, and system identification [10]. Additionally, efforts have been made to address the security and privacy concerns associated with the collection and storage of real-time operational data in the DT environment [11].

DT of EDS should be equipped with load flow calculation and state estimation techniques to achieve the objective of grid management in real time. Load flow calculation is a fundamental analysis in EDS that determines the steady state operating conditions, including voltage magnitudes, phase angles, and power flows. Various techniques have been proposed to solve load flow equations, ranging from traditional Newton-Raphson and Gauss-Seidel methods to more advanced optimization-based algorithms [12], [13].

State estimation plays a crucial role in assessing the real-time operating conditions of EDS. By combining measurements from different monitoring devices, state estimation algorithms can accurately estimate the system's state variables, even in the presence of measurement errors and uncertainties [14]. Several state estimation methods have been proposed in the literature, including weighted least squares, Kalman filtering, and particle filtering [15]. These methods aim to improve the accuracy and timeliness of state estimation, enabling operators to make informed decisions regarding system operation and control.

To cope with the limitation of proprietary software, inflexibility in adapting to diverse grid configurations, and constraints in real-time scalability, the flexible application for the development of DT of EDS is proposed. Contrarily to

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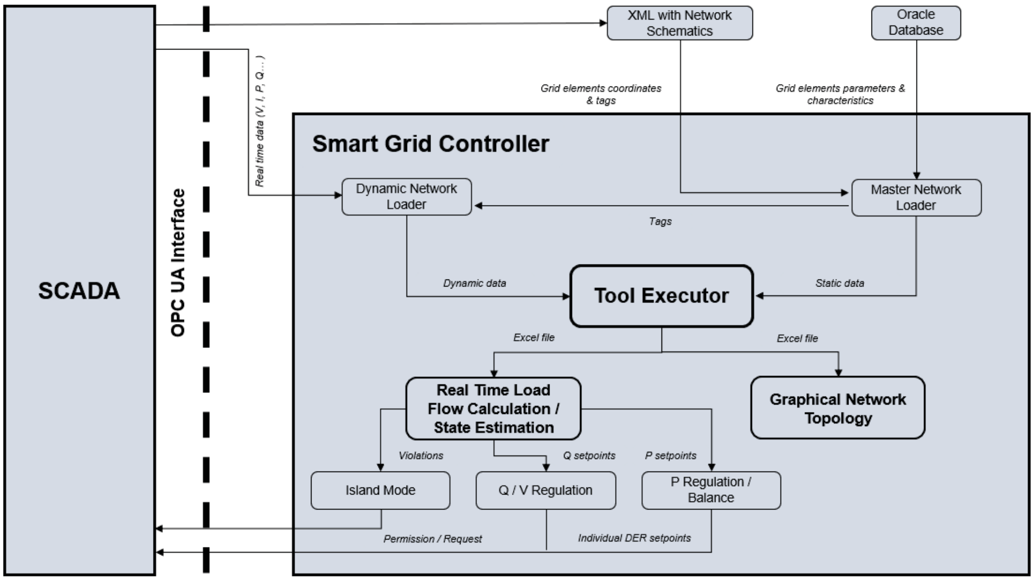

Fig. 1 SGC architecture

most of the work in literature our approach provides novelty by using entirely open-source Python libraries to develop SGC application for the creation of DT of EDS, which offers tools for grid observability and Smart Recursive Load Flow (SRLF) calculation, tested on real grid in Sarentino Valley, Italy. The developed SGC application has the potential to select any portion of real EDS for creating the DT by redefining the boarders, providing the possibility to run test scenarios i.e., blackout and island mode operation for future work. Developed DT is able to retrieve static data about power system's structure from the database and real time measurements and states of components from SCADA by Remote Terminal Units (RTUs). At the same time DT is flexible enough to increasingly connect to other data sources such as IoT nodes and meters with various protocols. In addition, the developed DT utilizes static and real time data to perform SRLF calculation and predictive state estimation of the loads in distribution networks.

II. CASE STUDY DESCRIPTION

A. Demo Site

The demo-site is a distribution system located in Sarentino Valley, in the center of South Tyrol, north of Bolzano, Italy. Being the largest municipality in the region in terms of area, it is known as the ”green lung of South Tyrol”. The primary DSO oversees an extensive network spanning 8,608 kilometers, encompassing High Voltage (HV), Medium Voltage (MV), and Low Voltage (LV) lines. This network serves approximately 230,000 customers. Due to the mountainous terrain, a diverse array of hydroelectric plants is integrated into the grid, contributing a total installed power of 348 MW out of the combined 616 MW from Medium and Low Voltage production sources [16]. The DSO network supplies 50 sub-DSOs, and the study is performed on the MV and LV grid supplied by the HV/MV Sarentino substation which consists of:

- 2 x 66/20 kV transformers 25 MVA.
- 5 MV feeders
- Petersen coil (neutral connected to earth by impedance).
- 1 HV Hydroelectric plant, 29 MVA connected to HV busbar.
- 10.4 MW of installed production in the MV and LV grid (3.6 MW hydroelectric, 2.7 MW PV and 4.1 MW thermal power generation).
- 2 sub-DSOs connected to MV grid, with another 10.6 MW of installed production (9.8 MW hydroelectric).
- 24.6 MW of total loads (3000 LV and MV customers).

B. System Architecture and Components

The primary components of the system include the real grid, SGC and SCADA. The real grid consists of various elements such as generators, transformers, transmission lines, loads etc. Most of these elements are integrated with Remote Terminal Units (RTUs) and Plant Central Regulator (PCRs) for the exchange of real time data and measurements with SCADA.

The SGC is a software application, entirely based on Python language, installed on a dedicated server which is hosted at the Control Centre of the DSO, operating on a Windows Server2019 platform. Its aim is to add functionalities to the existing SCADA in a flexible manner. SGC is developed within the EU project Flexigrid. Its key responsibilities encompass:

- Ensuring the stability of the involved EDS.
- Coordinating the balance between requested and generated power.
- Implementing algorithms for power and voltage regulation.
- Managing the power dispatch of Distributed Energy Resources (DER).
- Executing the transition from on-grid to off-grid and vice versa, while preventing disruptions to connected loads.

Fig. 1 shows the architecture of the SGC application. The SGC needs to monitor the electrical quantities related to

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loads and generators, as well as the status of every element displaced within the EDS in real time in order to achieve the above-mentioned objectives and to enable the DSO to identify and solve possible issues in advance. The developed methodology for real-time SRLF calculation and predictive state estimation of the loads has enabled the DSO to achieve the mentioned objectives and will be discussed in more detail in Section III. Additionally, this approach enables the operator to perform fast analysis and simulation of various hypothetical scenarios, as time restriction in distribution system management is crucial.

SCADA is a category of software applications used to oversee and manage industrial processes. It involves gathering real-time data from remote locations to monitor equipment and conditions. SCADA is integrated with RTUs and PCRs to facilitate the two-way exchange of data.

C. Data Acquisition and Integration

Data acquisition and integration are pivotal in the development and operation of the DT for EDS. In this subsection, we outline the process of gathering and integrating data from various sources to ensure the accuracy and reliability of the DT model.

Real-time data and measurements are sourced from the SCADA system, which is integrated with RTUs and PCRs. RTUs located in substations provide a range of measurements, including active and reactive powers, voltage, and current levels of the starting and ending lines, and other relevant parameters at different points within the distribution network. The real-time data from both the PCRs and RTUs are managed by the SCADA through bidirectional communication protocols following the IEC-61850 standard.

The exchange of real-time data between the SGC interface and SCADA occurs through the OPC UA communication protocol, with SGC acting as the Client and SCADA as the Server. Furthermore, the results of SGC processing can be accessed by SCADA through bidirectional communication by reversing their respective roles. Fig. 2 illustrates the communication scheme between SGC, SCADA, and RTU/PCR devices.

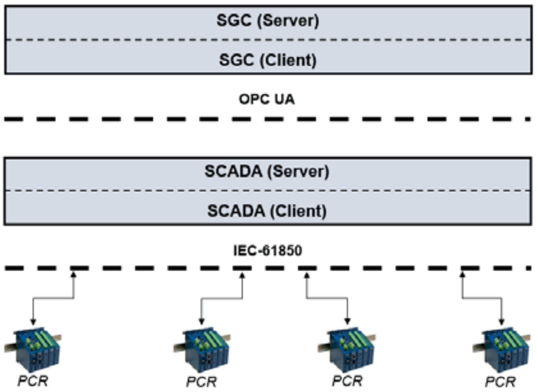

Fig. 2 Communication scheme between SGC, SCADA and RTU/PCR devices

The grid network schematics are imported by SGC from SCADA in the form of an XML file. It extracts information about the network elements coordinates and OPC-UA tags for further analysis. The SGC requests electrical characteristics, parameters, and other static information about the grid elements from the ORACLE database via a query. This communication channel ensures that the SGC remains aligned with the actual conditions of the distribution system.

III. METHODOLOGY

In this section, the development of tools within the SGC application will be discussed. The developed tools are for grid observability, Smart Recursive Load Flow (SRLF) calculation, and state estimation of loads in the MV feeders of EDS. These tools require both static and dynamic grid data as input in the form of an Excel file. This file is structured with separate sheets for various element types such as external grid, generators, loads, bus bars, lines, transformers, switches, and so on. Each sheet contains information like the OPC UA tags, characteristics, parameters, connection with other elements, and real-time measurements for all elements of the same type. The Excel file is generated by gathering static grid data from the Master Network Loader module and dynamic grid data from the Dynamic Network Loader module within the SGC application.

Fig. 1 demonstrates that the XML file can be imported by Master Network Loader module from SCADA at any time. This file contains information about the coordinates and OPC-UA tags of EDS elements for real-time data queries from the OPC server (SCADA). In addition to the XML file, the Master Network Loader requests electrical parameters, characteristics, and other static information about the EDS elements from the ORACLE database through a query. By utilizing all the provided information, the Master Network Loader runs a recursive topology search algorithm to understand the network topology and boundaries of the EDS under study. This process generates a Json file that combines information about the characteristics, parameters, tags, geolocation, and connections of all EDS components. The produced Json file is then fed to the Tool Executor module.

Real-time measurements along the grid elements are retrieved by SCADA through RTUs, as shown in Fig. 2. RTUs are connected to the electrical elements of the EDS, each distinguished by specific tags, and they provide a comprehensive range of measurements, including active and reactive powers, as well as voltage and current readings at the starting and ending lines. These measurements are then transmitted to the Dynamic Network Loader module of SGC through OPC UA communication, which already contains the tags of grid elements provided by the Master Network Loader. The real time measurements along the grid elements are transferred to Tool Executor for the generation of input Excel file for the developed tools. Tool Executor combines the static grid data in Json format coming from Master Network Loader and dynamic grid data containing real time measurement coming from Dynamic Network Loader to generate the Excel file.

The Tool Executor module of the SGC enables the DSO to develop the DT of any grid portion by selecting the borders for

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a more focused study and testing hypothetical scenarios. After the selection of boarders, the Excel file is tailored accordingly to contain the topology, static and dynamic data of the selected grid portion, which is then fed to Graphical Network Topology and Real Time Load Flow Calculation/State Estimation tools for calculation and analysis.

The Graphical Network Topology tool is used for building the graphical network topology. It takes Excel file as an input and utilizes pandapower APIs (open-source Python library) to enable the visual inspection of EDS, as the geo-location of elements such as busbars, lines, switches, etc. is respected. It enables the DSO to have observability over the periphery and topology of the EDS in order to provide ancillary services and test hypothetical scenarios.

The Real Time Load Flow Calculation/State Estimation tool performs real-time SRLF calculation and state estimation of loads in all MV feeders by taking Excel file as an input which contains real-time measurements along EDS elements under study. It enables the DSO to perform fast analysis and simulation of various hypothetical scenarios without incurring high expenses for system upgrade, as time restriction in EDS management is crucial. This tool utilizes pandapower API to perform load flow calculations which is based on Newton Raphson Method.

The measured active and reactive power at MV busbar of each feeder in EDS is retrieved through the input Excel file. State estimation of loads in each MV feeder is accomplished through the SRLF calculation, all without the need for additional metering devices or system upgrades. This objective is achieved by initially setting the active power of all loads in each MV feeder to zero in order to calculate the active power at MV busbar of each feeder with zero loads, through load flow calculation (pandapower API). Then the error between the measured and calculated active power is calculated. Subsequently, the active power of loads in each feeder are scaled up or down by their nominal apparent power in the recursive loop, aiming to minimize the error between the measured and calculated (via load flow) active power at MV busbar of each feeder in each iteration. The error (ϵ) between the measured and calculated active power at MV busbar of each feeder is calculated using (1):

$$\epsilon = Pcalc_n - Pmeas_n \tag{1}$$

Scaling factor for scaling active power of loads in MV feeder is calculated using (2):

$$sf_n(i) = sf_n(i-1) + \frac{a * \left(Pcalc_n(i-1) - Pmeas_n(i-1)\right)}{\sum_j Sload_j} \tag{2}$$

where *n* is MV feeder number, *i* is iteration number, *j* is load in *nth* MV feeder, *a* is a variable, *Pcalc* is feeder's active power at the MV busbar (calculated by load flow), *Pmeas* is feeder's active power at the MV busbar (real time SCADA measurement), *Sload* is nominal apparent power of load, *sf* is scale factor (0-1), applied to the nominal apparent power *S* of all loads *j* in the *n* feeder.

The value of a is based on the calculated active power with loads at nominal and zero values before the recursive loop and it is calculated using (3):

$$a = \begin{cases} -1, & \text{if } Pcalc_{nominal} \geq Pcalc_0 \\ 1, & \text{if } Pcalc_{nominal} < Pcalc_0 \end{cases} \tag{3}$$

where $Pcalc_{nominal}$ is feeder's active power at the MV busbar, calculated by load flow with loads at nominal value, $Pcalc_0$ is feeder's active power at the MV busbar, calculated by load flow with zero loads.

Active power of loads in all the feeders is scaled up or down by their nominal apparent power in the recursive loop using (4). The updated values of active power of loads are used in the load flow calculation to calculate $Pcalc_n$ at MV busbar of *nth* feeder.

$$Pload_j = sf_n * Sload_j \tag{4}$$

Same process of scaling is repeated for the reactive power of loads to finally estimate the states of loads in the EDS.

IV. RESULTS

In this section, the performance of tools developed inside SGC application is discussed. The developed tools are for grid observability, SRLF calculation and state estimation of load in all MV feeders as discussed in the previous section. The Graphical Network Topology tool inside SGC application takes Excel file as an input and provide the graphical network topology of the EDS.

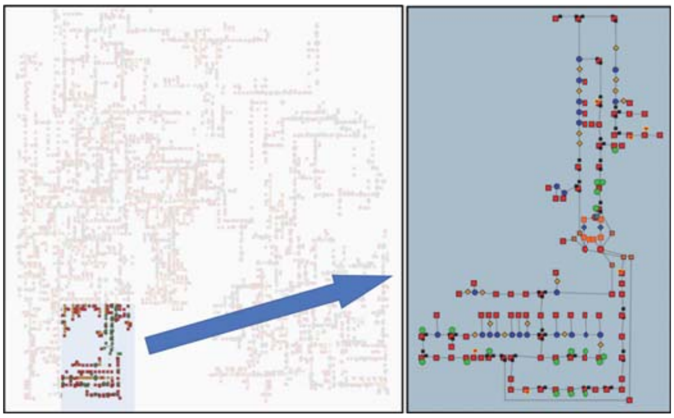
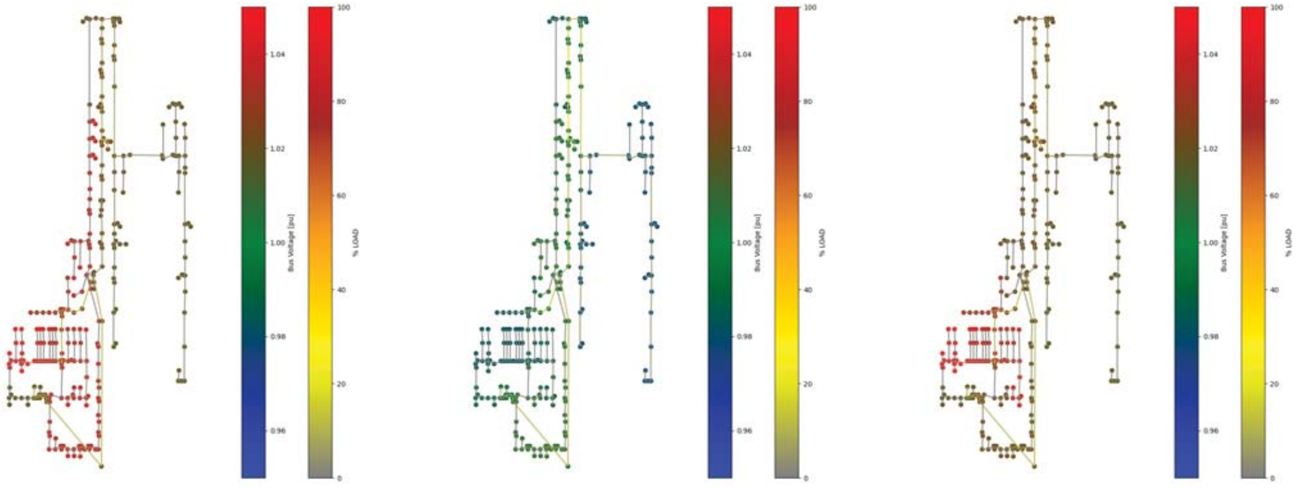


Fig. 3 EDS visualisation with selected grid portion

Fig. 3 shows the graphical representation of the whole EDS in Sarentino Valley, Italy with the network topology of the selected grid portion for the focused study. It can be seen in Fig. 3 that the geolocation of EDS elements such as busbars, line, switches is respected in the selected grid portion.

The Real-Time Load Flow Calculation/State Estimation tool performs SRLF calculation for the state estimation of loads in all MV feeders. This tool has been tested under three cases: high voltage, low voltage, and normal case. It estimates the states of loads in MV feeders by minimizing the error (within a certain tolerance) between the measured active/reactive power



(a) High voltage case (b) Low voltage case (c) Normal case

Fig. 4 Three test cases

and the calculated active/reactive power (via load flow) by upscaling or downscaling the loads in the recursive loop.

The evolution of the scale factor for upscaling or downscaling the active/reactive power of loads in all MV feeders in each iteration is recorded. Table I displays the evolution of the scale factor for active power (sf_P) and reactive power (sf_Q) in the test cases.

TABLE I
EVOLUTION OF SCALE FACTORS

	Case 1 (sf_P)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.121	0	0.124
iteration 2	0	0	0

	Case 1 (sf_Q)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.056	-0.111	0.038
iteration 2	0	0	0

	Case 2 (sf_P)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.316	0	0.041
iteration 2	0.313	0	0

	Case 2 (sf_Q)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.054	-0.118	0.050
iteration 2	0.050	0	0

	Case 3 (sf_P)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.121	0	0
iteration 2	0	0	0

	Case 3 (sf_Q)		
	Feeder 1	Feeder 2	Feeder 3
iteration 1	0.056	-0.115	0.035
iteration 2	0	0	0

The scale factor for some of the feeders in the test case is 0, indicating that the loads in the MV feeder will remain at their nominal value. This is because when the scale factor is 0, the loads in the MV feeder are not scaled, resulting in a negligible difference (ϵ) within 10KW tolerance, between the calculated active/reactive power (via load flow) and the measured active/reactive power at the MV busbar of the feeder. In some cases, the specified tolerance is achieved as early as the 1st and 2nd iteration.

Fig. 4 shows the graphical representation of selected grid portion under study for the test cases: high voltage, low voltage, and normal case, with the level of current and voltage along line and busbars. The circles represent the busbars and straight line represents the lines in the grid. Color scheme is used to represent the percentage of line loading along line and voltage level along busbars in the grid.

V. CONCLUSION

In this paper, we proposed an SGC application to develop the DT of EDS. The application is developed using open-source Python libraries, and it offers tools to DSOs for enhanced grid observability and state estimation of loads beyond the typical scope of real-time measurements along MV feeders. The proposed SGC application is tested on the real EDS in Sarentino Valley, Italy, and can be integrated with the SCADA of any grid with a given network topology, electrical parameters, and characteristics of the grid elements. The application has the potential to select any portion of EDS for creating the DT by redefining the boarders, enabling a focused study of grid portion, and providing the possibility to run hypothetical scenarios i.e., blackout and island mode operation for future work. The tool of SGC application for grid observability provides a graphical representation of the network topology respecting the geolocation of grid elements. One of the primary tools of the SGC application involves performing SRLF calculations. Based on the results, it conducts state estimation of loads within certain tolerances in the MV feeders without incurring high expenses for additional metering devices or system upgrade. Leveraging the information generated by SRLF, voltage, current, and active power control modes for DER makes it possible, the aim of pursuing more stability and reliability of the EDS.

ACKNOWLEDGMENT

This research has received funding from the European Union's Horizon project FLEXIGRID, under Grant Agreement No 864579. The author would like to thank Edyna Srl (DSO) for the data provided.

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