HAC: Hardware Design for a Smart-Home and Smart-Grid Decentralised Load Management System

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***Abstract*—The growth of energy demand and decentralised renewable energy generation (e.g. photovoltaic, eolic) can lead to electric grid imbalances requiring extra investments in the electric grid infrastructure. One of the goals of Smart-Home and Smart-Grid solutions is to solve this issue. The majority of the solutions are focused on centralised load management. Furthermore most of the Smart-Home and Smart-Grid publications analyse the topics from the application point of view so that there is a lack of specific descriptions of the infrastructure and of the used technology. SUPSI has proposed and verified a decentralised and innovative Smart-Grid approach. To demonstrate the feasibility of this approach a custom HAC (Household Appliance Controller) and a communication infrastructure has been developed. This paper describes this design, and its use in several pilot projects performed in Switzerland (Swiss2Grid, RiParTi 2.0, HCD 2.0) which in their turn have demonstrate the feasibility and the benefits of a decentralised Smart-Grid management.**

Keywords. *Smart-Home, Smart-Grid, Hardware Design, Powerline comm., LonWorks, Decentralized solution*

I. INTRODUCTION

The integration of the ICTs [1] in the whole energy chain (production, distribution and consumption) has laid the groundwork to the whole Smart-Grid topic. During the last years the broadly and well accepted Smart-Grid concept has shown important potentialities in the research and market fields, giving interesting advantages for end-users and for environmental issues [2] [3] [4].

One of the well accepted definitions of Smart-home is proposed by Intertek[1] "A dwelling incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed." Nowadays Smart-Home cover different branches [5] like Healthcare, Security, Comfort, Entertainment and Energy Optimisation. This paper is focused in the field of Energy optimisation.

In the perspective of energy management, the Smart-Home term means a building equipped with smart devices able to monitor the behaviour of a household appliance and interact with it. Smart-Home as well as described in [6], can be seen as an intelligent collaborative agent of the network instead of an isolated passive members of the grid.

One of the first devices that turned our homes into Smart-Homes without the awareness of the user was the introduction of residential Smart Meters installed by the Distribution System Operators (DSO) allowing an effective monitoring of the energy [7].

Most of research publications related to Smart-Home or Smart-Grid are more focused in the application side, however the infrastructure and the hardware used are less explained in detail [8] [9]. This is also the case of publications from related projects conducted by SUPSI University like Swiss2Grid [10], RiParTi 2.0, and previous pilot projects.

This paper aims to fill this gap describing the infrastructure solution and proposing an alternative approach for the electronic hardware (HW) used in Swiss2Grid, RiParTi 2.0 projects for a smart-grid decentralised load management systems.

The hardware named *Household Appliance Controller (HAC)* is a custom designed HW that monitors and manages the behaviour of the appliances in a house. Contrary to the traditional Advanced Metering Interfaces (AMI) (Commercial products) or smart grid controllers [11], the HAC distinguish itself adding additional features and direct connectivity with the house appliances (e.g. intelligent independent appliance control) which are starting to be directly integrated in appliances and commercialised [2].

The purpose of the HAC is to have a very flexible hardware platform intended to cover most of the present and future applications. It is used to demonstrate and test smart-grid systems and algorithms like the novel Smart-Grid Decentralised Load Management System idea [12] [13] [14]. HAC is also proposed as a new hardware system not available on the market with a cost effective approach. HAC inspired also the design of further projects like HCD 2.0[3] and

[1]http://www.housingcare.org/downloads/kbase/2545.pdf

[2]V-ZUG Home: Your link to the future. http://www.vzug.com/ch/en/int_novelties_2015_vzug_home_anschluss

[3]http://www.alpiq-intec.ch/news-storys/storys/stories.jsp?story=tcm:122-114001

GridSense®[4].

The HAC, managed by an intelligent algorithm, handles the energy consumed and produced inside the house, thus allowing to stabilise the network in a decentralized way[12] [13] [14].

HAC can be installed between any household appliance and the AC mains. Thanks to the different provided interfaces (RS232, RS485, CAN, ISO/IEC 14908-3) it can be integrated in almost any appliance (e.g. heat pumps, water heaters, battery-to-grid systems, electric vehicle chargers, Solar Panels) in Smart-Grid systems (retrofitting). Fig. 1 illustrates how the HAC can be used with the appliances in the household.

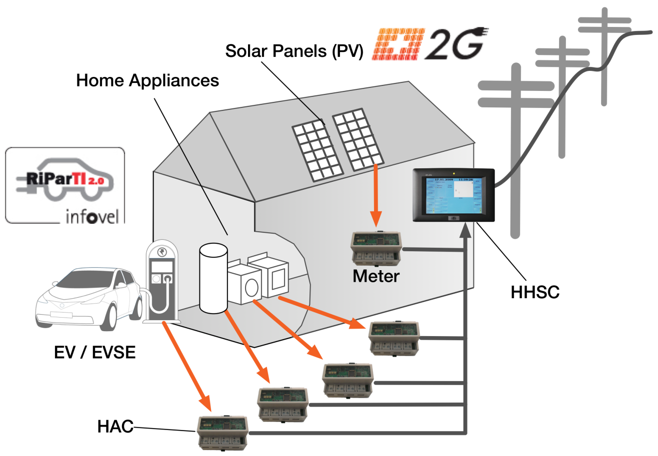

Fig. 1. HAC Installation and related projects

Another important element of the system is the Household Simulator and Controller (HHSC). This device is responsible to set preferences of the user and visualise relevant information. In a first design step of the project the HHSC also integrated the algorithm that manages the HACs, allowing faster algorithm development iterations. In a future step the algorithm will be embedded in every HAC so that each device will be completely autonomous. The HHSC consists of an industrial panel-PC based on x86 architecture with a Linux operating system. Each HAC communicates to the HHSC trough a powerline network.

II. Home Appliance Controller - HAC

A. *Hardware functionalities*

As mentioned before to demonstrate the feasibility of the grid load management in a decentralized way, a dedicated and flexible acquisition device that could be interfaced with the largest number of devices was necessary. SUPSI designed the HAC with all the needed features. The HAC is the core of the whole system giving information of the behaviour of every connected household appliance device to the algorithm. It can acquire many electrical values and can also manage the devices connected to it. This section will describe the features of the HAC that are also summarized below.

- ARM Cortex-M3 (STM32F105) μC
- Smart meter
  - Voltage: 195V...265V, 0.1V resolution, 0.2% accuracy
  - Current: 0.1A...40A, 3 mA resolution and 0.5% accuracy
  - Energy: 0.1% Wh accuracy
  - Phase: 0...360°, accuracy 0.5°
- Frequency 49...51Hz, 1mHz resolution, accuracy 0.02%
- (LonWorks Protocol ISO/IEC 14908) communication
- CAN Interface (Galvanically Isolated)
- Digital I/Os (Galvanically Isolated)
- 2 GB SD Card for logging, configuration and FW update
- RS232 and RS485 Interface (Galvanically Isolated)
- Relay (230Vac 2A)
- User Interface (3x LEDs, 3x Buttons)

Fig. 2 illustrates the HAC 3-Phase Block Diagram.

The HAC integrates an energy acquisition circuit able to acquire voltages and currents from the 3-phases grid with an accuracy better than 0.2% and 0.5% respectively. The accuracy value is improved by a circuit calibration.

Since the variations of the AC mains frequency are very small and there is no "low-cost" metering system offering a resolution better than 50mHz, a dedicated frequency acquisition circuit with an accuracy better than $\pm$ 4 mHz was designed.

A galvanically isolated RS232 and RS485 interfaces are also available. RS232 for debugging purposes and RS485 to connect any future device that supports this interface. A CAN Interface is also available to give the possibility to communicate with devices that have this interface such as Battery Management Systems (BMS). It is also galvanically isolated. A Digital PWM Input Interface is provided to connect any duty-cycle based sensor, both differential or single-ended. This interface is also galvanically isolated. The HAC include also a small relay (230Vac 2A) that can drive small loads or bigger load trough an external circuit breaker. The HAC provides a SD Card interface up to 2GB (FAT) for data logging, system configuration and FW update, a dip-switch, LEDs and push-button for status-diagnostic purposes.

[4]GridSense® is a registered mark of ALPIQ

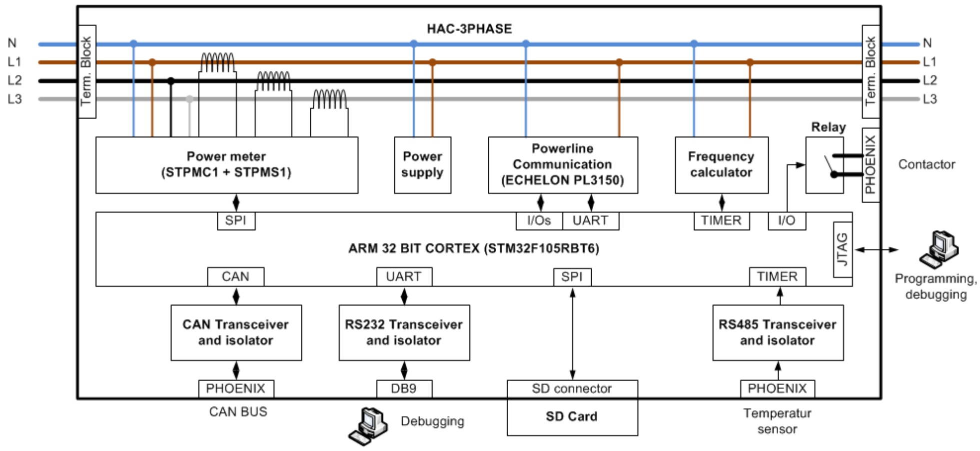

Fig. 2. HAC 3-Phase block diagram

B. Software implementation

An embedded real time software is implemented as a modular C program and makes no usage of any operating system. The processing of asynchronous and periodic events is managed by a prioritized event loop which dispatches the events to the appropriate handlers. For the LonWorks powerline networking, the ShortStack 2.1 API is integrated in the microcontroller and works together with the PL3150 smart transceiver running the ShortStack 2.1 microserver firmware. This is described in Figure 3.

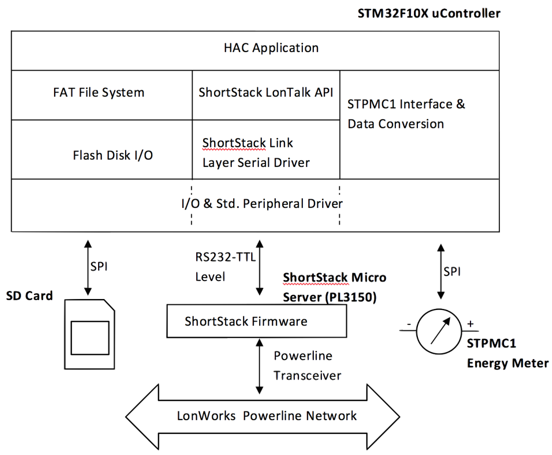

Fig. 3. HAC software architecture

On the acquisition side The HAC is oversampling the data acquired by the sensors, so that a better accuracy can be achieved. This data is later statistically processed to grant the desired value to be propagated in the network.

C. Resulting Device

The resulting HAC device developed is illustrated in Fig. 4.

For an easy installation, the HAC has an enclosure compatible with DIN EN 60715. The wiring of the unit is made via screw connectors (sustaining a current up to 63A).

Fig. 4. HAC 3-Phase system

D. Synchronized data transfer between HACs and HHSC Using PLC

The communication between HACs and HHSC is assured by the LonWorks powerline communication protocol. This narrow-band protocol is widely used for home and Building Automation systems and it is characterized by a baud rate of 5.6 kbps. Other narrowband PLC solutions as mentioned in [15] were also studied, but from the implementation and design point of view (access to *detailed technical* information for the design) LonWorks provided the best solution. The key points for the choice were robustness and reliability [16] [4]. Every HAC sends messages with electrical values information to the HHSC every 30s. The frame sent contains 43 Bytes composed by a payload of 30 Bytes and an overhead of 13 Bytes. The HAC transmits 6 packet every 30 seconds giving a throughput of 68.8 bps for every device. This is illustrated in Fig. 7. The network bandwidth saturation is reached with more than 81 devices.

A functionality designed over the LonWorks protocol is the data sampling synchronization between the HAC modules in the network. Indeed, the HHSC unit sends using a broadcast message a synchronisation event every 1 hour to ensure an accuracy with a jitter smaller than 100ms. This feature is requested by the algorithm for a precise analysis of voltage, current, frequency and power of the grid in different points of the network at the same time.

The HAC transmits the results using the Powerline network to the HHSC. To preserve the integrity of the network without saturating the communication with the risk of message loss, the system incorporates a communication algorithm able to send the data shifted in different time slots for every HAC in the resending period of 30 seconds (See Figure 7).

E. PLC Coupling Capacitor Analysis

During the tests a problem related with the the physical layer of the powerline data transmission was encountered. The ANSI/CEA-709.3 PHY is defined by Echelon[17]. There are two different coupling techniques: Isolated and non isolated. All the coupling solutions (3-phase, 1-phase, connected to E or N) are based on this two techniques. Both techniques uses a X2 capacitor (C101 in Fig.5) to couple the data to the main line. The HAC integrate this solution and used a X2 capacitor from EPCOS (series B32921). Fig. 5 illustrates the powerline circuit.

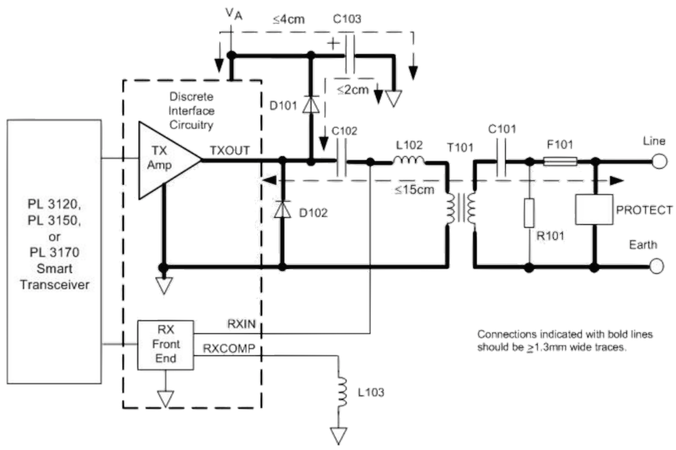

Fig. 5. Echelon Powerline reference design circuit

During the field tests the powerline network has shown an almost linear degradation of the amount of received messages over time by the central unit. Starting from about 2000 messages/day at installation time, after 5-6 months the messages has shown a degradation of the sent messages dropping down almost to 0. This was observed for all the installed devices. The problem was investigated and it was found that the reason resided in the coupling capacitor (C101). General purpose X2 capacitors (not only from EPCOS) are designed to be used in parallel with the AC mains and not in series with it. If used in series with the main line to couple high frequency signal they are affected by a fast degradation in the capacitance value. [18].

The degradation is not a concern in typical Echelon powerline applications, e.g. home and building automation. In this cases the amount of messages sent trough the powerline is almost defined by the actions taken by the home resident (turn on/off the lights, raise and lower the blinds) that can be quantified in less than 20 transactions per day. In the case of the HAC the number of messages sent is higher, overstressing the the X2 capacitor (C101) highlighting the degradation of the data transmission.

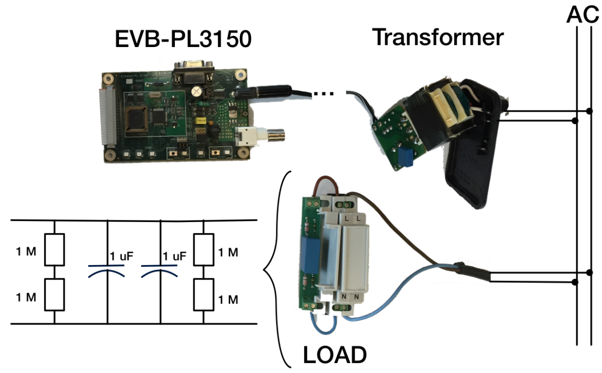

Fig. 6. Echelon Powerline test circuit

To validate our reasoning additional tests were made. We build a node in the laboratory using the Echelon EVB-PL3150. Fig. 6 depicts the HW and load circuit used. The C101 capacitor was over stressed with a dedicated SW that sent the same information as the HAC on the main line but 12 times/sec instead of 12 times/min as illustrated in Fig. 7. The main line impedance was also reduced with 2x1uF (cap B32923C3105M heavy duty) capacitors in parallel between L and N. The result of the capacitance degradation over time is shown in Fig. 8. The initial 100nF value dropped to less than a half after about 3 months. For this kind of application a heavy-duty X2 capacitor is suitable.

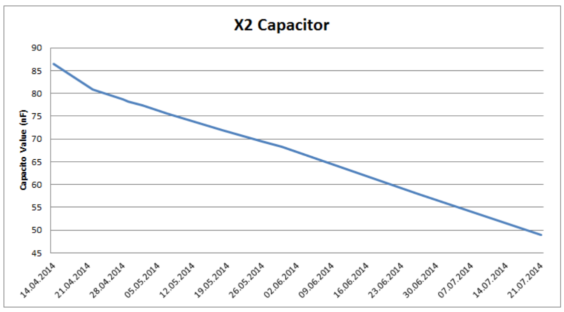

Fig. 8. Capacitor degradation

F. Frequency Analysis

Another goal of the project was to find a correlation between the main line frequency and the load at a given time. Having established that the variations in the frequency of the network are small (tens of mHz of the nominal value), a circuit that could also monitor the frequency with a resolution

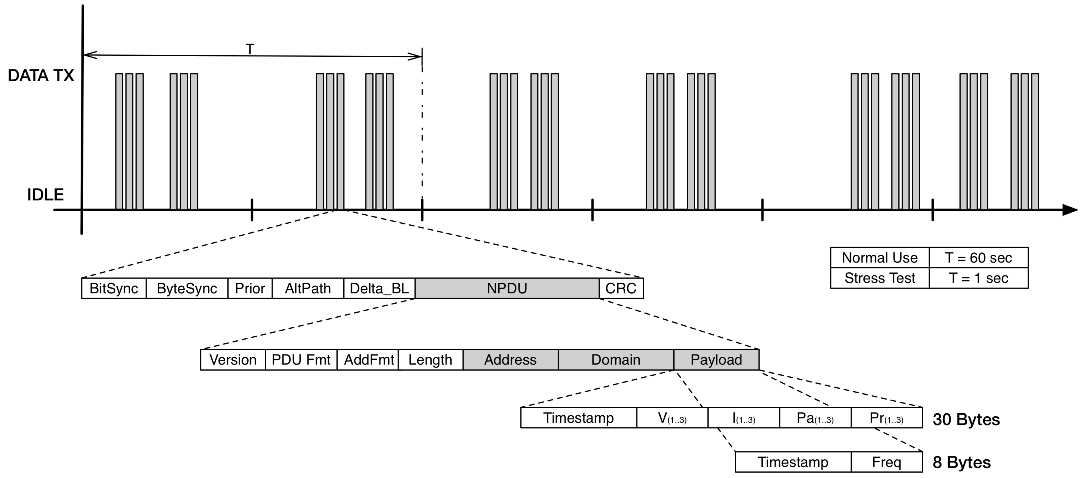

Fig. 7. PLC data packet

of 1 mHz was designed.

The accuracy analysis of the measured HAC frequency was made with the Power Sentinel 1133A instrument of Arbiter Systems Inc. Some of the characteristics are the frequency accuracy <1 ppm (0.0001 %) of reading, Vrms 0.02 % of reading or 0.002 % range, Arms 0.03 % of reading or 0.003 % range. The test was conducted over a period of 72 hours for a total of 10500 samples. Fig. 9 illustrates the deviation of the values obtained by the HAC compared with the Power Sentinel 1133A. The analysis of the frequency has shown a normal standard deviation of 0.01%.

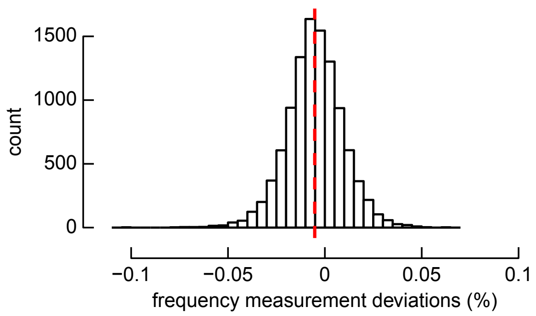

Fig. 9. Frequency analysis

III. Application Example

The great versatility of the HAC can be applied to several type of research and pilot projects. The HAC has been successfully integrated to heat pumps, electric water heater, stationary batteries and electric cars [10]. In this section we present an example of application where the HAC has been successfully integrated.

RiParTi 2.0

The goal of the pilot project RiParTi 2.0 is to test a smart home recharging infrastructure for electric vehicles. Typically, when a vehicle is connected to an electrical outlet, charging starts immediately at a fixed charging power, ending only when 100% of the battery capacity is reached. The vehicle charger is then inactive until the next use.

Within this project a HAC device was integrated in a EV Supply Equipment unit (EVSE). The HAC is able to start, stop and change the charging rate of the EV charger embedded in the vehicle by using standard Mode 3 IEC 62196 signals. The HAC measures and transmits local voltage and power values to a fully-decentralized multi-objective optimization algorithm, which minimizes user tariff costs and ensures local grid stability by altering the charging schedule [10]. These objectives are satisfied by learning the user behaviour, estimating state of charge and plugged period and by using the HAC communication interface to delay and modulate the EV charge process. A typical vehicle charging cycle controlled by the algorithm is shown in Fig. 10.

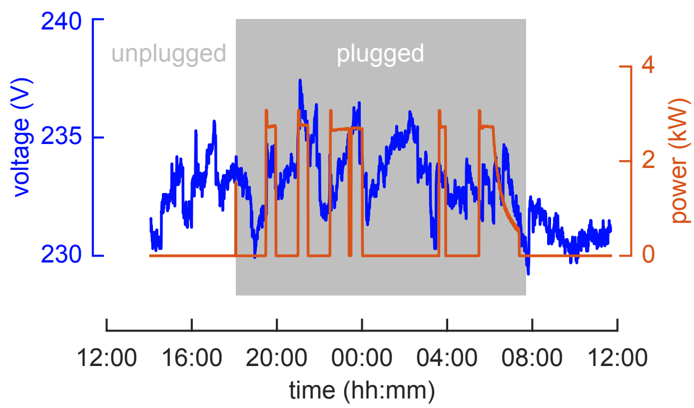

Fig. 10. Example of smart charge process. Blue: voltage at plug, brown: active power. EV plugged period is depicted by the grey area.

The grey area shows the plugged period when the EV is connected to the EVSE (18:00-08:00). When the EV is connected to the EVSE the algorithm estimates the state of charge and the plugged period. Then it schedules the charging process. Using a forecasting method, the algorithm predicts the time course of voltage for the next 24 hours and uses it to plan the charging cycle. The actual charge profile is shown in red. The algorithm interrupts several times the charge, preferring periods with high local voltages. During these periods low power values are expected at the local LV transformer [13]. Fig. 10 describes the power derating occurring at the end of charge (constant voltage charging mode near 100% SOC). The algorithm correctly schedules the charging, ensuring the complete charge of the vehicle.

Swiss2Grid

Within the Swiss2Grid project [10] was applied the HAC and the controlling algorithm to heat pumps, water heaters and stationary batteries installed in residential households. Similarly to the RiParTI 2.0 project Swiss2Grid used the voltage measurements as a driving signal to the energy management algorithm. The HAC controls the devices by using the output AC relay, which is connected to the DSO disable input of the heat pump controller or is connected to the water heater power supply. For the stationary batteries the control signals are transmitted to the battery inverter via the RS232 interface and the battery state of charge (SOC) is monitored via the CAN interface.

IV. Conclusion and future work

In this paper is described a system that has allowed to demonstrate the functionality of a flexible hardware that has been used in several projects. With the proposed and validated Hardware was possible to prove the feasibility of a Decentralised Load Management System.

After the test and the evaluation of the HAC with the RiParTi 2.0, and Swiss2Grid projects new projects are being considered. The most recent project which integrates the HAC technology is the GridSense® project lead by ALPIQ-Switzerland, company specialised in the production, distribution and trading of electric power. GridSense® is an ongoing project started in 2014. The goal is to manage the grid with an artificial intelligence algorithm able to monitoring the grid and control household appliances and electric vehicles.

As future work one of the most challenging improvements of the HAC system will be embedding the A.I. algorithm in the HAC technology for a fully decentralised load management system. Moreover a remote Firmware and Software update through LonWorks Powerline network will be integrated.

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