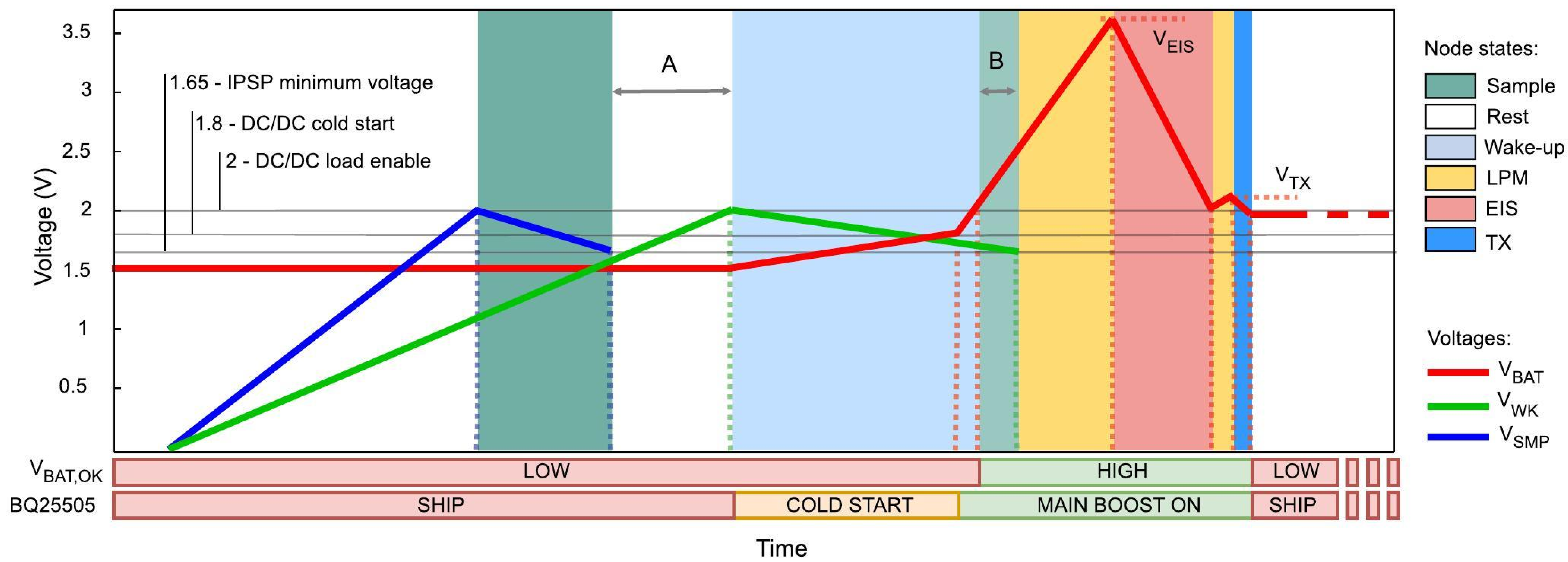

Fig. 2. Full battery-free, PMFC-powered EIS application cycle. The voltage levels of all supplies (V_{WK}, V_{SMP}, V_{STOR}), sensor node, and component states (outlined in Section III-C). The current draw from the three supplies is reported in Table II. A refers to the time margin between OCV sampling and wakeup to ensure a correct OCV measurement, while B is where supply handoff happens.

TABLE I
CAPACITOR MODELS TESTED IN PMFC-POWERED DC/DC COLD START

Symbol	Capacitance [μF]	Nominal voltage [V]	Leakage [μA]	Producer and part number
C_1	47	63	3	Elna, RE3-63V47MF3
C_2	470	16	3	Rubycon, 16YK470M8X11.5
C_3	10000	6.3	3	Panasonics, EEUFC0J103S
C_4	470000	5.4	13	Eaton, PHV-5R4V474-R
C_5	1000000	3.9	4	Eaton, PHVL-3R9H305-R

TABLE II
SENSOR NODE CURRENT DRAW IN ITS DIFFERENT STATES

Node state	SC draw from wakeup [nA]	SC draw from storage [nA]	Components avg current from storage	Duration [s]	Notes
Sample	0.8	0 or 0.82[a]	–	x[b]	
Wakeup	2.02	0.02	325 nA	x[b]	BQ active (cold-start/output disabled)
LPM1	–	1.66	705 nA	x[c]	BQ active + voltage monitors MCU in LPM 4.5, SVS enabled
EIS	–	1.66	1.75 mA	722.2	BQ active + voltage monitors EIS + MCU active
LPM2	–	1.66	705 nA	x[c]	BQ active + voltage monitors MCU in LPM 4.5, SVS enabled
TX	–	1.66	23.54 mA	0.112	BQ active + voltage monitors LoRa TX + MCU active
Rest	–	0.82	5 nA	Until next wake-up	BQ in ship mode

[a]As rest mode (0.82 nA), if $V_{\mathrm{BAT}}>1.65$ V (IPSP supply voltage, Section III-C2), 0 nA if $V_{\mathrm{BAT}}< 1.65$.
[b]Depends on harvested power input and C_{WK}, C_{SMP} dimensioning.
[c]Varies based on power input, charging speed, storage leakage and ultimately task-triggering voltage.

entails bacterial multiplication and biofilm formation on the cell's electrodes. Cell startup was done by flooding the PMFC reactor with water and leaving it undisturbed/unloaded until OCV stabilized above 0.6 V. Whenever OCV overcame this threshold, the PMFC was considered *active* and the colony sufficiently settled to source power, as the cell could comfortably cold start the dc–dc converter. During its active period, the reactor was provided with common plant fertilizer and a glass of water (137 ml) whenever soil dried up and OCV started dropping. If OCV stopped recovering above 0.6 V after watering, the cell was deemed *inactive*, as it failed to cold start the dc–dc converter.

B. Application Context

Battery-free electronics relying solely on energy harvesting sources for their functioning often run out of stored energy and incur in power failures. While some tasks can quickly be interrupted, and their progress can be recovered through intermittent computing strategies, other tasks, such as message exchanges and measurements, require uninterrupted execution not to yield erroneous results. *Energy-aware* scheduling only triggers uninterruptible tasks when the stored energy is sufficient to ensure their continuous execution. This requires uninterruptible task energy profiling and state of charge estimation. When capacitors are used as energy storage for the sensor node, the state of charge can easily be determined through their voltage V_{STOR}. By previously knowing task energy requirements, we evaluate the V_{STOR} threshold that triggers the task and ensure completion.

The proposed sensor node is to be deployed on a large scale outdoors and indoors for a cost-effective, maintenance-free plant monitoring solution. This battery-free application is meant to be self-powered through the electrodes of the PMFC, which it also uses for EIS measurements. It has the potential to empower farmers to monitor plant-and-soil health down to the single plant, providing a dense map of the crop state and ensuring resources are used only when and where they are needed most.

The full application cycle of our sensor node, composed of the sequence of states listed in Table II, can be seen in Fig. 2. In further detail, this sensor node executes two subsequent uninterruptible tasks, an EIS sweep and then a LoRa transmission, in an *energy-aware* fashion. This is done by triggering EIS execution when the storage is charged to V_{EIS}, and transmission (TX) when storage grows to V_{TX}. These two thresholds (see Section IV-E for how we obtained them) ensure that the storage can complete the task before discharging down to V_{MIN}, where the node enters *rest state*.

In the rest state, no power is harvested from the PMFC, and the leftover storage energy, which enters rest charged at V_{MIN}, is safeguarded thanks to the node's ultralow power consumption in rest mode (see Table II). Rest state was integrated as it was proven that periodically unloading PMFCs, in what we call *intermittent harvesting*, benefits both the length and the quality of PMFCs' power production (see Section II). As mentioned in